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Review of the impacts of introduced ornamental fish species that have established wild populations in Australia

Prepared by:

J. Corfield, NIWA Australia
B. Diggles, DigsFish Services
C. Jubb, Burnbank Consulting
R. M. McDowall, NIWA
A. Moore, Spring Creek Environmental Consulting
A. Richards, Meyrick & Associates
D. K. Rowe, NIWA

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Author affiliations:
J. Corfield. NIWA Australia Pty. Ltd., P.O. Box 359, Wilston, Brisbane, Australia (now at Hydrobiology Pty. Ltd., P.O. Box 2050, Milton, Queensland 4064, Australia)
A. S. Moore. Spring Creek Environmental Consulting, 50 Wettenhall Circuit, Calwell, ACT 2905, Australia
B. K. Diggles. DigsFish Services Pty. Ltd., 32 Bowsprit Beach, Bribie Island, Queensland 4507, Australia
A. Richards. Meyrick & Associates Level 4, 12-20 Flinders Lane, Melbourne, Victoria 3000, Australia
C. Jubb. Burnbank Consulting Pty. Ltd., Canberra, Australia
R. M. McDowall. NIWA Ltd., PO Box 8602, Christchurch, New Zealand
D. K. Rowe. NIWA Ltd., PO Box 11-115, Hamilton, New Zealand

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Executive Summary

The introduction and spread of alien (non-native) species in various parts of the world is regarded by many as a major threat to global biodiversity and hence ecological sustainability. In Australia, introductions of species such as the cane toad, prickly pear, foxes, rabbits, and common carp are among the higher profile biological invasions. However, few people are aware that small, freshwater fish species, including some used as ornamental fish in ponds and aquaria, can also cause damage to Australian environments and species.

Many ornamental fish are brought into Australia each year for stocking into home aquaria or garden ponds and between 12 and 14% of Australians are thought to keep aquaria. It is inevitable that some of these ornamental fish end up in natural waterways and although many don't survive, some have established feral populations. Accordingly, there has been a rise in the number of exotic freshwater ornamental fish species establishing wild populations in Australia over the past 20-30 years. Of the 41 alien fish species currently known to have established populations in Australia, up to 30 are now thought to have arrived in the country via the ornamental fish trade. This is a relatively large number of new species and there is growing concern over the potential for one or more of these to create an expensive environmental problem.

Risk assessment frameworks have been developed in Australia for ornamental fish and are used to determine whether it is safe to import a particular species into the country. However, risk assessments are based on information obtained overseas and, in many cases, can be of limited value in predicting the likelihood of environmental impacts in Australian waters. Data from field studies of the species in Australian waters are required to ground-truth such risk assessments. In addition, the ornamental fish industry will require more robust data on the impacts of these species than that provided by risk assessments if it is to provide tangible help with the management of these fish.

This report on the environmental impacts of feral ornamental fish in Australian water was therefore commissioned by the Department of the Environment, Water, Heritage and the Arts to provide an objective review of current knowledge of the impacts of freshwater ornamental fish in Australian waters. In was prepared by a number of experts in the relevant fields (viz. fish ecology, genetics, taxonomy, pathogens, management, and environmental economics) to ensure a comprehensive approach and to ensure a robust and unbiased approach was peer reviewed by two senior academics as well as a representative from the conservation sector and another from the ornamental fish industry. In addition, the review was opened to the public for submissions over a six week period in late 2007.

The review provides new maps of the known geographic distributions for 27 of the 30 ornamental fish species thought to have established populations in the wild in Australia. These maps revealed the presence of species clusters around several major population centres

indicating that human activity is the main vector for the spread of such species and that public information programmes are urgently required to counter this. Good maps are also a key component of the management of feral fish species, indicating where control or containment needs to be targeted and for detecting any long term changes in distribution. However, the existing databases for mapping fish distributions in Australia are either restricted in scope (by State borders or catchment boundaries) or not well supported. The lack of a national mapping system for Australia constitutes a major gap in the ability of management agencies to liaise effectively over the control of feral fish species. It contrasts with the situation in other countries (e.g. USA and New Zealand) and needs to be addressed if progress is to be made nationally. Species mapping and identification also revealed a need for field studies to confirm the taxonomy of three species, to determine whether three of the 30 species still exist in the wild, and to decide whether any of the species present at only one or two locations can be eradicated before they spread further.

Basic data on the biology of each of the 23 species reviewed are presented even though these are lacking for many species. Both global and Australian studies on impacts were over-viewed within the context of impact assessment methodologies and the often impractical task of obtaining unequivocal proof of impact. The impact assessments indicated that although unequivocal proof of impact is lacking for all species, the available data for nine raised considerable concern. These nine species are therefore high priorities for future field investigations to provide convincing evidence of impacts, or not.

In addition to potential ecological impacts on endemic habitats and biodiversity, many of the feral ornamental fish may also pose pathogenic and genetic risks for the Australian aquatic fauna. These potential impacts were investigated and it is apparent that, while the Australian Quarantine and Inspection Service manages the importation and quarantine of introduced fish to prevent the introduction of new pathogens to Australia, there is little knowledge of the parasite and pathogenic loading of ornamental species now in the wild. Clearly some surveillance and monitoring is required to identify whether new parasites and pathogens are present in any of these wild populations of introduced ornamental fish. Genetic impacts are restricted to the possibility of hybridisation and the creation of new strains with increased hybrid vigour and new traits that could result in environmental damage. This potential problem is fortunately restricted to the very few places where two or more, closely-related ornamental fish species co-occur in the wild. In lieu of eradication, periodic monitoring is required at these few locations to detect any such genetic changes.

The economic assessment of the ornamental fish industry clearly showed its overall size and value as well as the relative importance of certain species. It is apparent that many ornamental fish species are regularly imported because the facilities for live-production in Australia are limited and this may increase the risk of introducing unwanted pathogens. Overall, there have been few studies on the economic impacts of pest fish species in any country mainly because the data are lacking and successful fish control and management methods are few in number and limited in application. Because future management of such fish will be highly dependent on economic evaluations of control options, a suite of economic methods and tools are presented to address this gap and to identify future data requirements for such evaluations.

The review of management tools available for the control of feral populations of ornamental fish indicated how few are available and of those that are available how restricted in application they are. Furthermore, there is increasing opposition to the use of some of these because of ethical considerations, fear based on a lack of information and the risk of collateral environmental damage. Because of these limitations, management is more focussed on public education than control at present, but there is a clear need to develop more effective monitoring methods and fish control tools targeted at small as against large fish.

In summary, this review has identified a number of key issues for the future management of feral ornamental fish in Australia that need to be urgently addressed. The recent proliferation of wild populations of ornamental fish in Western Australia and Queensland is matched globally only by the high number of such species in the southern states of the USA. Although progress will clearly involve targeted education to change public perceptions about the dangers of ornamental fish, it will also require a nationally coordinated approach to stop the current situation from deteriorating further. In this respect, cooperation will be required between the various Federal and State management agencies as well as between State authorities because the spread of such fish within rivers will ignore State boundaries. There is a grave danger that one or more of these introduced fish species will become another pest like the common carp and create another legacy of degraded environments and costly controls.

1. Introduction

1.1 Reason for this review

The introduction and spread of alien (i.e. non-native) species in various parts of the world is regarded by many as a major threat to global biodiversity (Vitousek et al. 1997; Sakai 2001; Kolar and Lodge 2001; Lee 2002; Dudgeon et al. 2006) and this threat applies substantially to freshwater fishes (Courtenay 1990; Courtenay and Stauffer, 1990; Courtenay and Moyle, 1992: Fuller et al. 1999; Canonico et al. 2005). There are many instances where the introduction of an alien species, ranging from a micro-organism to a vertebrate, has had unexpected consequences for the native fauna and flora in both terrestrial and aquatic ecosystems (IUCN 2001; Global Invasive Species Programme webpage). When reviewing global causes of species decline, Reid et al. (2005) noted that the introduction of non-native, alien species is the major cause of extinctions. This is especially so in freshwater ecosystems such as lakes (Sala et al. 2000).

In Australia, the introductions of species such as the cane toad, prickly pear, foxes, rabbits, and rodents are among the higher profile biological invasions (Low 2001), although many Australians are also now aware of potential threats posed by large, introduced freshwater fish such as common carp (Roberts and Tilzey 1997). It is less likely, however, that Australians are generally aware of the potential ecological impacts of other introduced freshwater fish species, especially the small fish species prevalent in the freshwater aquarium trade.

Small fish species can be just as great a threat to native biodiversity as large fish species. For example, *Gambusia holbrooki* (mosquitofish) was introduced to Australia for the control of mosquito larvae. Although this fish is relatively small (maximum size < 6 cm), it has now been linked to ecological impacts on the native freshwater fauna in most of the countries to which it has been introduced throughout the world (IUCN 2001). The potential impact of other small fish that are introduced into the wild may also be significant and small fish should not be discounted just because of their size, or the fact that they are ornamental and relatively benign in an aquarium or pond environment.

Many ornamental fish are brought into Australia for stocking into home aquaria or garden ponds and between 12 and 14% of Australians are thought to keep aquaria (McNee, undated). These fish generally have no obvious value arising from them being released into Australia's waterways. Despite this, there has been a steady increase in the number of exotic freshwater ornamental fish species that have become established in Australian waterways over the past 20-30 years (Arthington et al. 1999;

Lintermans 2004; Koehn and Mackenzie 2004). It is noteworthy that ornamental fish species account for a majority of the recent fish introductions to Australian freshwater ecosystems (Fig. 1.1) and constitute a 'new wave' of fish introductions that far exceeds that which occurred in the late 1800's with the influx of European immigrants.

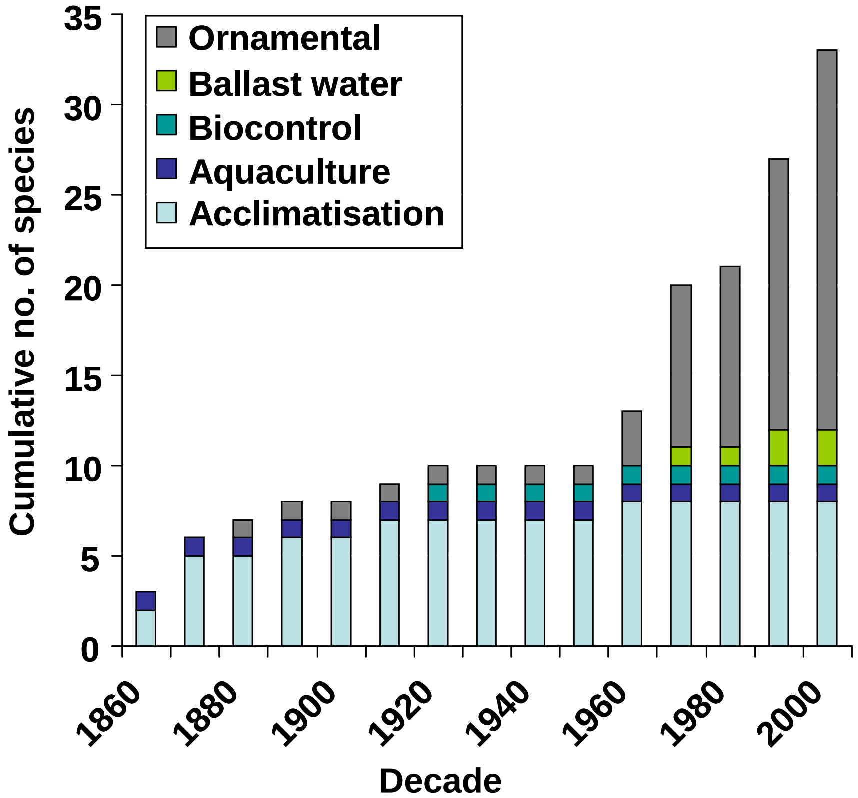

Figure 1.1: The cumulative number of alien freshwater fish species reported in the wild per decade, categorised by the sectors responsible for importation (courtesy Dr T. Peacock, Invasive Animals CRC as derived from Lintermans (2004)).

A recent study conducted by Casal et al. (1999) documented the status of exotic (now termed alien) freshwater fish in Oceania and found that although Australia had the highest diversity of freshwater fish in the Oceania region, the proportion of alien species that were established in the wild (10%) was among the lowest of the countries considered. However, Casal et al. (1999) stated that 11 of the most commonly introduced species in Oceania were considered to have adverse effects in at least one country and five of these were ornamental fish species (i.e. *Oreochromis mossambicus*, *Tilapia zillii*, *Carassius auratus, Xiphophorus hellerii* and *Poecilia reticulata*). The impacts of such ornamental fish species in Australia have received far less attention than those of common carp, but already a number of species (e.g., goldfish, tilapia, oriental weatherloach and a few poeciliids/platys) have been associated with some impact in some locations (Lintermans et al. 1990; Lintermans 1993; Arthington 1986, 1989, 1991; Arthington and Mitchell 1986; Arthington and Bluhdorn 1994; Arthington and Cadwallader 1996).

Risk assessment and management frameworks have been developed in Australia for ornamental fish (e.g. Arthington et al. 1999; Kailola 2000; Bomford and Glover 2004; DAFF 2005) and are used mainly for assessing the risk of importing a particular ornamental species. The underlying principles of such risk assessments are invasion theory, particularly views espoused by Moyle and Light (1996a,b). Their theory is underpinned by the biological properties of different fish species in relation to both their potential invasiveness and the nature of the receiving environment. However, not all scientists specialising in invasive fish ecology support the use of all these attributes. Invasion ecology is an inexact science and there are many uncertainties in it as well as different ways of assessing risk, none of them perfect. For example, the risk assessment framework developed by McDowall (2005) for New Zealand was preceded by a critical review of the attributes associated with invasiveness listed by Moyle and Light (1996a). McDowall (2005) only incorporated a subset of these attributes into his risk assessment framework. Of these, physiological temperature tolerances of the species were considered the most reliable criterion for evaluating the likely success of introductions in New Zealand.

The risk of a species becoming established in the wild is also related to 'propagule pressure' and to the number of pathways by which a species can be spread to the wild (Kolar & Lodge 2000; Lodge 2001; Ricciardi & MacIsaac 2001). This is particularly relevant for ornamental fish in the sense that the most popular species for aquaria can be expected to be as widely and densely distributed as human residences, with each aquarium or ornamental pond constituting a potential source of propagules for establishment of these species in the wild. However, apart from the match between habitat and species tolerances, establishment in the wild will also depend on the number of pathways by which such fish are transferred from aquaria or ponds to natural waters. The latter is clearly a key process in the invasion of ornamental fish and many of the various pathways by which alien fish are released into natural waters have been well described by Lintermans (2004). Propagule pressure and dispersal pathways are therefore key components of risk assessments relating to the invasive potential of alien fish populations. Both need to be considered alongside species-specific impacts to determine the potential for a species to become a pest. In this sense a pest fish is defined as one which impacts on native fauna and habitats in a wide range of situations and which also has the potential to become widely established. Ideally risk assessments applied to fish predict their potential to cause adverse impacts as well as to spread widely because such attributes are not correlated for fish species as readily as they are for alien plant, insect or mammal species that invade terrestrial environments.

Applying such risk assessment frameworks to alien fish species for which there is a paucity of data can result in erroneous findings or interpretations and lead to a precautionary approach which may be unnecessary. On the other hand, available information often does not allow the application of rigorous protocols that provide sufficiently secure protection from adverse impacts. While a precautionary approach to managing invasive species is seen by many as wise or even essential, the ornamental fish industry is a key stakeholder that could be negatively affected by adverse publicity surrounding the perceived impacts of ornamental species introduced and/or established in Australian waterways. If the ornamental fish industry is to contribute in a meaningful way to ensuring effective management of established ornamental fish in Australia, it is likely to require more robust data on the impacts of these species than that provided by risk assessments. Furthermore, Australian environmental legislation leans heavily towards the protection of biodiversity (e.g., the EPBC Act 1999) and the application of this legislation will require much better scientific information on the effects of ornamental fish species on native biodiversity. Apart from the need for more robust data on the potential environmental impacts of ornamental fish, the ornamental fish industry has economic and social values and any environmental consequences of introduced species need to be considered within this context.

In summary, the issue of the impacts of established ornamental fish in Australia's waterways combines ecological, social, economic and legislative elements and there may be major knowledge gaps in terms of potential or actual impacts that need to be filled before effective management can be determined and/or the support from key stakeholder groups obtained. It is on this basis that the Department of the Environment, Water, Heritage and the Arts (DEWHA) commissioned a study to review the current status and potential ecological threats posed by the freshwater ornamental fish species that have already established breeding populations in Australian waters. The purpose of this review is to identify key gaps in knowledge so that the DEWHA and the ornamental fish trade can develop a joint approach to managing the environmental consequences of the introduced species.

Although an assessment of gaps in knowledge of the environmental impacts posed by ornamental fish is required, a key component of this review is a socio-economic appraisal of the use of these fish and of the gaps in knowledge of their economic and social costs and values. This is a novel, but necessary, component of impact assessment, and is designed to assist managers of aquatic resources to better understand the issues. This will result in the ornamental fish industry obtaining a clearer picture of the extent of this management issue and their potential role in addressing it.

To maintain a balanced and wide-ranging approach to the issue of whether ornamental fish pose a threat to the native Australian freshwater fauna, a number of experts in the various fields have helped prepare this report. For example, the economic chapter was prepared by Anya Richards and Charles Jubb for Meyrick & Associates, a firm of economists with specialist expertise in the field of assessing the economic and social costs of environmental problems. An expert on fish diseases (Dr Ben Diggles) prepared the chapter covering the potential threats from the spread of parasites and pathogens, while Andrew Moore, who has researched alien fish, especially the impacts of *Gambusia* in Australia, mapped the species distributions and considered the genetic implications of the introduction of ornamental fish into Australia. Drs Jamie Corfield, Bob McDowall and David Rowe, all with the National Institute for Water and Atmospheric Research Ltd (Australia and New Zealand) are fish biologists with collective expertise in alien fish and prepared the remainder of the report.

Another key factor helping to maintain a balanced approach during this study was the establishment of a review panel comprising four people, representing key stakeholders and including the ornamental fish trade, the scientific community and conservation interests. Such a review panel was established and charged with reviewing the report and ensuring that it presents an unbiased viewpoint.

Personnel involved are:

- Professor Angela Arthington is a senior academic with Griffith University and has specialised in assessing the ecological impacts of introduced fish into Australia over many years.

- Professor Bob Lester from the University of Queensland is also a senior academic with specialist knowledge of fish parasites and disease issues.

- Mr Andreas Glanznig is a senior policy analyst with the World Wildlife Fund (Australia) and has specialist knowledge of the effects of introduced species (including freshwater fish) on the conservation of Australian ecosystems.

- Jared Patrick is the owner and manager of Bay Fish (www.bayfish.com.au) a wholesale distributor of ornamental fish and is a senior representative of the Ornamental Fish Industry in Australia.

1.2 Scope of the review

By the late 1980s, over 1,000 fish species had been brought into Australia since European settlement (McKay 1989). Similarly, McNee (no date) indicated that 1,181 alien species of mainly freshwater fish had been recorded in Australia over the past 40 years but only 481 of these are on the current permitted import list. More alien freshwater fish will have been introduced since these reports, however, this report deals only with ‘ornamental’ fish species involved in the freshwater aquarium and garden pond industry. Throughout this report we use the term ‘ornamental fish’ as opposed to ‘aquarium fish’, as the latter implies exclusion of fish stocked into garden ponds.

Currently there are over 450 ornamental fish species still on the official Australian importation list, with 200 individual species and 30 genera (encompassing 750 species) included on the live import list. Assessing the risks posed by these species would require a much larger and more long-term study than the present review, so some restrictions on the scope of species to be covered was required. Lintermans (2004) noted that of the 34 alien fish species that had established feral populations in Australian waters, 22 were thought to have come into the country via the ornamental fish trade. Accordingly, this review only covers alien aquarium or ornamental pond fish species established in Australian freshwater systems. The term ‘established’ means that a breeding population exists somewhere in the wild in Australia (i.e. its future existence is not dependent on stocking). The term ‘ornamental fish’ is used to describe small fish kept as pets in either home aquaria or in garden ponds. This review does not include marine species, or fish species introduced via ballast water discharge, or sport fish introduced into the wild in Australia including salmonids (which are covered as part of a parallel study). Neither does it include established alien fish species such as roach, common carp, redfin perch, and tench, all of which are not aquarium or ornamental species.

This report also covers only those species that are firstly confirmed as being established in the wild and, secondly, which were listed by Lintermans (2004). The reason for this is that some of the documented releases of ornamental fish into natural waterways in Australia may not result in successful establishment and there are likely to be other introduced species that have not become established at this point in time. One additional species (rosy barb, *Puntius conchonius*) not listed by Lintermans (2004) was added to this list because of advice from the Department of Agriculture, Fisheries and Forestry (DAFF) that it was now established in Australia. The 30 ornamental fish species reported as now being established in Australian waterways are listed in Table 1.1. The species covered by this report are indicated along with those present on the DEWHA live import list and thus currently allowed to be imported to Australia without a permit.

Table 1.1: List of ornamental freshwater fish species known to be established in the wild in Australia (source data [1]Kailola (2000), [2]Lintermans (2004)), including the species reviewed here, the *species currently on the Part 1 list of the DEWHA 'live import schedule' (i.e. not requiring a permit for importation) and the dates when the species were first recorded as being established in the wild (where known).

	Common name(s)	Scientific name	Sources	When first recorded as being established in the wild	Species reviewed in this report
Family Cichlidae					
1	Hybrid cichlid	*Labeotropheus/Pseudotropheus*	2	2001	Yes
2	Jewel cichlid	*Hemichromis bimaculatus*	1,2	2000	Yes
3	Victoria Burton's haplochromis	*Haplochromis burtoni*	1,2	1998	Yes
4	Black mangrove or Niger cichlid	*Tilapia mariae*	1,2	1978	Yes
5	Redbelly tilapia	*Tilapia zillii*	1,2	1980s	Yes
6	Blue tilapia	*Oreochromis aureus*	1		No
7	Mozambique tilapia or mouthbrooder	*Oreochromis mossambicus*	1,2	1970s	Yes
8	Oscar	*Astronotus ocellatus*	2	1998	Yes*
9	Three-spot cichlid	*Cichlasoma trimaculatum*	1,2	1998	Yes
10	Jack Dempsey	*Cichlasoma octofasciatum*	1,2	2004	Yes
11	Firemouth cichlid	*Thorichthys meeki*	1		No
12	Banded cichlid	*Heros severus*	1		No
13	Redhead cichlid	*Vieja synspila*	1		No
14	Red devil	*Amphilophus labiatus*	1,2	1992	Yes
15	Midas cichlid	*Amphilophus citrinellus*	1,2	1992	Yes
16	Convict cichlid	*Archocentrus nigrofasciatus*	1,2	1978	Yes
17	Blue acara	*Aequidens pulcher*	1,2	2000	Yes*
18	Green terror	*Aequidens rivulatus*	1		No
19	Pearl cichlid	*Geophagus brasiliensis*	1		No
Family Poeciliidae					
20	Green swordtail	*Xiphophorus hellerii*	1,2	1965	Yes*
21	Platy	*Xiphophorus maculatus*	1,2	1970s	Yes*
22	Sailfin molly	*Poecilia latipinna*	1,2	1969	Yes*
23	Guppy	*Poecilia reticulata*	1,2	1970s	Yes*
24	Caudo, one-spot livebearer	*Phalloceros caudimaculatus*	1,2	1970s	Yes
Family Osphronemidae					
25	Three-spot, blue or golden gourami	*Trichogaster trichopterus*	1,2	2000	Yes*

Family Cobitidae					
26	Oriental weatherloach	*Misgurnus anguillicaudatus/mizolepis*	1,2	1984	Yes
Family Cyprinidae					
27	Goldfish	*Carassius auratus*	1,2	1876	Yes*
28	Rosy barb	*Puntius conchonius*	1		Yes*
29	Sumatra barb	*Puntius tetrazona*	1		No
30	White cloud mountain minnow	*Tanichthys albonubes*	2	2003	Yes*

There is some confusion over the scientific names for some species because of both changes in nomenclature and re-classification, as well as uncertainty as to which of several closely related species are actually present in Australia. Wherever possible, the most recent scientific names recommended in FishBase[1] (Froese and Pauly 2006) are used here. Overall, 30 species of ornamental fish have now been recorded in the wild (Table 1.1). This excludes gambusia (*Gambusia holbrooki*), which while closely related to both the sailfin molly and guppy, is not considered to be an ornamental species and will be dealt with separately. In addition to the continuing taxonomic revision of species names, some species readily hybridise, whereas captive breeding has created distinct strains for some species. This complicates impact assessment as the attributes of hybrids and strains may differ from those of their constituent species in unpredictable ways.

The dates when the species were first recorded in Australia indicate that only one species was known to be present in the wild before 1950, but two were reported in the 1960s, six in the 1970s, two in the 1980s, five in the 1990s, and six in 2000s. This pattern of increase no doubt reflects the increased sampling effort and greater attention now applied to such fish, but it also suggests that releases and establishment are still occurring and it indicates that more species can be expected to be found over the next decade.

Several families of fish contain a large number of ornamental fish species, none of which yet occur in Table 1.1. For example, there are many species of tetras belonging to the family Characidae that are popular aquarium fish. Similarly killifish belonging to the family Cyprinodontidae are also popular fish in freshwater aquaria. None of the species within either of these families (nor any of the alien rainbow fishes in the families Melanotaenidae or Atherinidae) are listed as occurring in the wild in Australia even though these species can be expected to be widely present within freshwater aquaria. It seems unlikely that these fish have not been released into the wild (either inadvertently or deliberately) along with both cichlids and poeciliids.

1.3 Aims and objectives of the review

The overall aims of this study are to produce a report that firstly presents an objective understanding of the environmental, economic and social impacts (both positive and negative) of introduced ornamental fish species that have established wild populations

[1] Fishbase (Froese and Pauly 2006) is an international database that attempts to list all known fish species and provide a summary of information on all these species as far as is known. It also provides access to the literature on each species. The authors of the summaries for each species are not provided only a bibliography of the source material. It is therefore assumed that the species summaries reflect this material accurately and that they are updated as new information is published.

in Australia, and that secondly contributes to a cooperative and constructive approach to the management of introduced ornamental fish species, particularly for the protection of threatened native species and natural ecological communities.

The main tasks and objectives for this study are to:

- Map the current distribution of each established ornamental fish species in Australia.

- Assess evidence of ecological impacts associated with the established ornamental fish species and the methods used to assess these impacts.

- Based on this analysis, identify knowledge gaps and prioritise the need to fill these, and recommend alternative approaches to monitoring, impact assessment and research that will provide greater certainty with respect to actual impacts.

- Review the importation status of the ten species currently on the Department of the Environment, Water, Heritage and the Arts' live import list (Part 1, Schedule: List of specimens taken to be suitable for live import – Environment Protection and Biodiversity Act 1999). This review will include a discussion of the implications of the 'do nothing' option, as against restricting some or all of these species from continued importation and sale in terms of likely ecological costs and benefits.

- Review control and eradication options for pest fish management in Australia. Given that few of the listed, established, ornamental fish have control and eradication strategies already devoted to them in Australia, DEWHA were keen to determine what could be learned from overseas experience or experience associated with control of non-ornamental aliens such as salmonids and common carp. As part of this review, we also comment on the extent to which current or proposed control and eradication methods relating to alien fish are socially acceptable.

- Estimate the value of the ornamental fish industry (including legal and illegal trade and subsidiary industries) and review studies of socio-economic cost/benefits carried out to assess other species in Australia. Assess the methods used to determine socio-economic costs associated with the impacts of alien species and establish the type of economic modelling that should be applied to ornamental fish based on the quantity and nature of data available. Identify and prioritise the knowledge gaps that need filling in order to carry out such modelling.

1.4 Introduction to the species reviewed

Consideration of the phylogeny of the fish families represented by the species in Table 1.1 can provide a useful background to the interpretation of differences between the species. In particular, it allows consideration of some of the major adaptive differences characterising and distinguishing them, including feeding modes, parental care of eggs and water temperature requirements.

The species are classified into five families, three orders and two super-orders of fish (Fig. 1.2). The super-order Acanthopterygii differs from the Ostariophysi primarily in that its species have spiny as against soft fin rays. However, the Ostariophysi also possess a more specialised auditory sensory system based on adaptations associated with the air bladder (e.g., Weberian ossicles connecting the bladder to the inner ear). A number of species within the Ostariophysi are also capable of chemosensory communication based on their ability to detect chemicals such as pheromones and fright substances (see University of Liverpool Fish webpage at www.live.ac.uk/~rickl/Fisheries_Web).

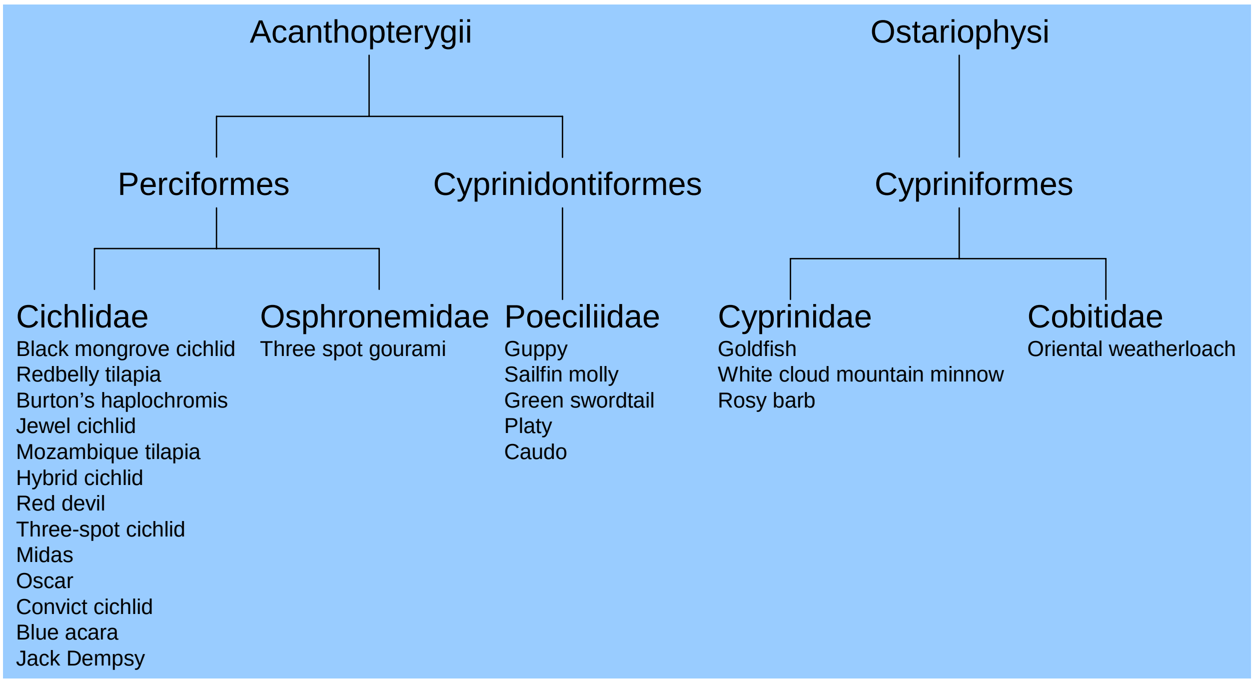

Figure 1.1: Phylogenetic relationships of the 23 species under review.

The spiny-rayed fish (Acanthopterygii) tend to dominate marine environments but some families (e.g., Cichlidae) have radiated widely within African lakes. In comparison, ostariophysian species, especially cyprinids, tend to occur more widely throughout freshwater habitats in Asia, Eurasia and in African waters, but do not occur in South America. Possession of specialised auditory and chemical communication systems is thought to help explain the success of the ostariophysian fish in freshwater as against marine environments (University of Liverpool Fish webpage), but it is clear from the proliferation of cichlids in African lakes and in many of the warmer freshwater environments in Asia, that many Acanthopterygian species also have adaptations which suit them well to a wide range of freshwater environments.

Fish species belong to both the Cobitidae and Cyprinidae families lack true teeth, hence these Ostariophysians are not specialised predators of highly mobile prey. Instead they possess pharyngeal teeth that allow them to 'masticate' food material. In general such feeding adaptations are associated with benthivorous behaviour and with feeding on plankton, plant matter and detritus. However, such fish are also able to feed on a wide range of benthic invertebrates and even small fish. In contrast, all the Acanthopterygian species listed in Table 1.1 possess teeth and can therefore be expected to actively prey on more mobile fauna throughout the water column.

The greatest number of species currently reported from the wild in Australia is from the family Cichlidae. Species within this family are generally characterised by one nostril positioned either side of the head and by nesting and/or parental guarding of the eggs and young. Many of the species within this family are also omnivorous, display aggressive behaviour and can remove vegetation from the substrate in the process of nest building (Midgalski & Fichter 1977). Approximately half of the cichlid species now present in the wild in Australia originated from South or North America, whereas the other half originated from Africa (Table 1.2). The taxonomy of this family is complex but Hougen (1994) provides a useful account of the main differences between groups that have evolved in the North versus South American continents and in Africa. In particular, he noted the greater number of taxa, the many reproductive strategies displayed and the wider size range for cichlids in Lake Tanganyika than in Lake Malawi and the very similar differences between cichlids from South versus North America. These differences imply that cichlids originating from Lake Tanganyika as against Lake Malawi and from South America as against North America can be expected to be much more specialised. In general, cichlids are warm-water fish found mostly in latitudes where summer water temperatures are above 20°C (Table 1.2).

Table 1.2: General characteristics of the 23 species of ornamental fish under review ([1]data from Fishbase).

Common name	Scientific name	Continent of origin[1]	Latitudinal temperature range[1] (°C)	Absolute range in temperature (degrees C)	Thermal classification based on latitudinal temperature range	Maximum fish size (cm)[1]	Spawning substrate or parental care of fry/eggs[1]
Family Cichlidae							
Hybrid cichlid	*Labeotropheus/Pseudotropheus*	Africa	------	--	------	----	-----
Jewel cichlid	*Hemichromis bimaculatus*	Africa	21-23	2	Stenotherm (warm)	14	-----
Victoria Burton's haplochromis	*Haplochromis burtoni*	Africa	20-25	5	Stenotherm (warm)	15	Mouth brooder
Black mangrove cichlid	*Tilapia mariae*	Africa	20-25	5	Stenotherm (warm)	40	Rocky substrates
Redbelly tilapia	*Tilapia zillii*	Africa	7-43	36	Eurytherm	40	Rocky substrates
Mozambique tilapia	*Oreochromis mossambicus*	Africa	8-42	34	Eurytherm	39	Mouth brooder
Oscar	*Astronotus ocellatus*	America	22-25	3	Stenotherm (warm)	40	Rocky substrate
Three-spot cichlid	*Cichlasoma trimaculatum*	America	21-30	9	Stenotherm (hot)	37	Nest guarder
Jack Dempsey	*Cichlasoma octofasciatum*	America	22-30	8	Stenotherm (hot)	25	Nest guarder
Red devil	*Amphilophus labiatus*	America	28-33	5	Stenotherm (hot)	24	Nest guarder
Midas cichlid	*Amphilophus citrinellus*	America	23-33	10	Stenotherm (hot)	24	Rock crevices
Convict cichlid	*Archocentrus nigrofasciatus*	America	20-36	16	Eurytherm	10	Range of substrate
Blue acara	*Aequidens pulcher*	America	18-23	5	Stenotherm (warm)	16	-----
Family Poeciliidae							
Green swordtail	*Xiphophorus hellerii*	America	22-28	6	Stenotherm (hot)	16	Livebearer
Platy	*Xiphophorus maculatus*	America	18-25	7	Stenotherm (warm)	6	Livebearer
Sailfin molly	*Poecilia latipinna*	America	20-28	8	Stenotherm (hot)	10	Livebearer
Guppy	*Poecilia reticulata*	America	18-28	10	Stenotherm (hot)	4	Livebearer
Caudo	*Phalloceros caudimaculatus*	America	20-24	4	Stenotherm (warm)	4	Livebearer
Family Osphronemidae							
Three-spot gourami	*Trichogaster trichopterus*	Asia	22-28	6	Stenotherm (hot)	15	Bubble nester
Family Cobitidae							
Oriental weatherloach	*Misgurnus anguillicaudatus*	Asia	10-25	15	Eurytherm	25	Range of substrates
Family Cyprinidae							
Goldfish	*Carassius auratus*	Asia	0-40	40	Eurytherm	60	Plant material
Rosy barb	*Puntius conchonius*	Asia	18-22	4	Stenotherm (warm)	14	Plant material
White cloud mountain minnow	*Tanichthys albonubes*	Asia	18-22	4	Stenotherm (warm)	4	-----

However, whereas most species have a somewhat restricted latitudinal native range (equating to an absolute temperature range of less than ten degrees Centigrade, the red belly tilapia and Mozambique tilapia both have a much wider latitudinal range than the other cichlids (i.e. equivalent temperature range of 34-36°C) and so can be expected to tolerate a much wider range of water temperatures. The three tilapia species (Genus *Tilapia* and *Oreochromis*) all grow to a large maximum size (40 cm), as does the three-spot cichlid and the oscar (Table 1.2). Other cichlids are somewhat smaller (10-25 cm maximum size).

The family Poeciliidae is characterised by species where fertilisation is internal, eggs are developed within the female body cavity and the young are therefore born live. In general, the species now present in Australian waters are all from central and South America and are also warm-water fish likely to prefer water temperatures higher than 20ºC (Table 1.2). They are mostly small fish with a maximum size of less than 16 cm (Table 1.2). This family includes the mosquito fish (genus *Gambusia*), which is an accepted pest in many countries outside its native range, including Australia.

The Osphronemidae differs from other families in that its species possess a specialised breathing organ connected to their gill chamber and derived from adaptations of the swim bladder (Midgalski & Fichter 1977). This enables them to obtain oxygen by gulping air and allows them to colonise stagnant waters where other fish dependent on gills alone could not survive. The Osphronemidae also build nests made of small bubbles. The single alien species now present in Australian waters (i.e. three-spot gourami) originated in southern Asia and, based on its native range, is also a warm-water species (Table 1.2). The three-spot gourami is also a relatively small fish.

The loaches (Cobitidae) also have a specialised organ for air breathing, but the labyrinthine organ used for this is connected to the intestine (Midgalski & Fichter 1977). Some species in this family (e.g., weather loaches) are known for their change in behaviour and increased activity when air pressure drops. This is thought to be related to the effects of changing air pressure on their labyrinthine organ. Although the oriental weatherloach originated in Asia, its latitudinal range is much greater than that of the three-spot gourami, and it can be expected to occupy a wider latitudinal range in Australia and to tolerate lower water temperatures than either the Poeciliidae or Osphronemidae.

The Cyprinidae are a diverse family and as with the Cobitidae lack teeth and spiny fin rays. They generally possess barbels which they use to detect prey or food within or on the bed of the waterbody they inhabit. This family contains carp (*Cyprinus carpio*), roach (*Rutilus rutilus*) and tench (*Tinca tinca*), which also occur in the wild in Australia. All three species of ornamental cyprinids now in Australia (Table 1.2) are from Asia and except for the goldfish have a similar temperature range to many of the Poeciliids. Hence, they too can be expected to prefer relatively warm-waters (i.e. over 20ºC).

In general, the species of ornamental fish in Table 1.2 can be classified by the water temperature range associated with their native latitudinal range into either stenotherms (i.e. they occur where the absolute temperature range is small to moderate, e.g., 2-10°C) or eurytherms (i.e. they occur where the absolute temperature range is wide e.g., 15-40°C). Eurytherms can by definition cope with a wide range of water temperatures and therefore have a potentially wider geographic distribution within Australia than stenotherms. Stenotherms are associated with a more restricted temperature range, which may be relatively hot or cold, or somewhere between these two extremes. Of the stenotherms listed in Table 1.2, those species associated with relatively hot maximum water temperatures (i.e. 28-33ºC) might be expected to have a more northerly potential distribution in Australia than the species associated with comparatively warm maximum water temperatures (i.e. 22-25ºC).

These differences among the families, and species within them, provide the main points of difference between ornamental fish and other alien fish in Australia such as salmonids, perch and carp. In general, the ornamental fish species are smaller and require warmer waters than the sport fish and none of them are specialised piscivores. However, the poeciliids, which are the smallest species, have some traits in common with mosquitofish (*Gambusia affinis* and *G. holbrooki*) both of which are known to have affected native fish in other parts of the world, including Australia (Arthington & Lloyd 1989; Moore et al. 2002; Morgan et al. 2004). Although the ornamental fish species now established in the wild in Australia display a number of differences to alien sport fish and fish introduced for mosquito control, international experience with alien fish introductions indicates that a careful, species-by-species analysis of evidence for impacts in the wild is required. Such information is a pre-requisite for the future management of these species.

2. Distribution of established ornamental fish species in Australia

2.1 Introduction

Before examining the known distribution of the 23 ornamental fish species established in Australia to date, it is important to define the Australian aquatic environment being considered. For the purposes of this study, the species of ornamental fish being investigated are primarily freshwater fish and do not include any saltwater ornamental species utilised in seawater aquaria. The environment in which the target species could occur therefore includes all the freshwater habitats within the continental landmass of Australia and the adjacent island of Tasmania. We have not included freshwater habitats in Australian offshore territories such as the Cocos-Keeling Islands, Torres Straits Islands, Lord Howe Island, Norfolk Island or Christmas Island. Although inland saline and brackish water lakes are included, coastal saltwater habitats in harbours and around the coastline are excluded. This distinction is practical rather than ecological as some freshwater species may well become adapted to brackish and saltwater habitats. For example, *Gambusia affinis* is an example of a small freshwater fish that readily adapts to full strength saltwater and which is now abundant among mangrove swamps in a number of New Zealand harbours (Mitchell 1985). Conversely, some saltwater species such as the dart goby (*Parioglossus marginalis*) are capable of inhabiting freshwater habitats (McDowall 2001).

There are several features of Australian freshwaters that, in our view, make Australia much more vulnerable to invasion by ornamental fish than neighbouring countries such as New Zealand to the southeast or Papua New Guinea to the north. Firstly, the Australian continent covers a vast latitudinal range and encompasses a wide range of climate zones (e.g., tropical, subtropical, temperate and arid). Secondly, there is a wide diversity of habitat types for freshwater fish in Australia, including rivers, lakes, streams, estuaries, billabongs, wetlands, brackish lakes, floodplains and thermal springs. This combination of broad climatic range and high habitat diversity means that there is a much greater chance of ornamental fish becoming established somewhere in Australia than in a more temperate country such as New Zealand or in a more tropical and latitudinally compressed country such as Papua New Guinea. Moreover, the low gradient of much of inland Australia means that there are large numbers of ponds and small lakes. There is therefore a greater likelihood that the environmental requirements of at least some alien fish species will be met somewhere in Australia. Hence the risk of ornamental fish species becoming established somewhere in Australian waters and subsequently spreading within and among them is much greater than in neighbouring countries. Over time, the species that establish founder populations in a restricted habitat may become adapted to a wider range of conditions and acquire the ability to spread well beyond what would currently be considered their original habitable range (e.g., Arthington 1991).

The detection of new incursions of alien species is therefore more important for Australia than for neighbouring countries, and distribution mapping will be required to determine the location and rate of spread of all species. In this chapter we present the known data on the distribution of the 23 ornamental fish species currently established in Australia. Maps provide a basis for identifying where incursions have already occurred and a baseline for future monitoring of species' spread. It should be noted that the distributions portray the region(s) within which reproducing populations have been discovered and not locations where their absence can be confirmed. Furthermore, it is acknowledged that many inland waters have not been sampled adequately to date, and that the status of the 23 ornamental fish species cannot be presented for these waters. These omissions reflect the paucity of data on fish occurrence in Australian waters and emphasize the need for a coordinated national database and sampling programme to record and hence monitor alien fish distributions. These distribution maps therefore need to be interpreted cautiously and although some trends are apparent, the reasons for them are speculative and will require further evaluation.

2.2 Collection of data

The main method for obtaining distribution data for the 23 established ornamental fish in Australia was through reviewing reports and scientific journal articles or syntheses of these. Some of the standard natural history texts that cover the fauna were also consulted (e.g., Merrick and Schmida 1984; Allen et al. 2002). In addition, data were elicited from individuals in federal, state and local government agencies, regional bodies and universities considered most likely to have access to such data, or who could direct us to more appropriate sources. Many of these individuals were identified through their publications on alien fish, although networks of contacts were also utilised to obtain additional contacts. Those contacted are listed in Appendix 14.

When sourcing distribution data from individuals, two email surveys were utilised. The preliminary survey was a simple questionnaire (Appendix 14.2) aimed at obtaining a basic understanding of the sources of information in each state and of gauging who, among those contacted, were willing to provide us with more detailed distributional data. A second questionnaire (Appendix 14.3) was then sent to those who volunteered to provide us with more detailed distribution data. This was to obtain a more precise indication of the location of water bodies containing each species within each state. The initial questionnaire was distributed to 32 people known to have some knowledge of ornamental fish in the wild. A 72% response rate was achieved but many respondents felt that the questions were too specific for them to be able to answer adequately and rapidly.

The detailed distribution data was incorporated into maps similar to those used by the Australian Society for Fish Biology (ASFB) and displayed on their website. We chose this format as it was likely to be familiar to many of the readers of this report. It was also one that did not reveal specific locations. This was considered important by the project team because publication of such information might result in problems for some land owners and raise the possibility that some individuals might exploit this information (e.g., to collect alien fish from the locations either for profit or to transfer them to new locations). Furthermore, the location of populations was often limited to either general areas (see Table 2.1) or to streams and rivers rather than to identifiable reaches within catchments. Consequently, it was not possible to provide more accurate indications of the location of species such as grid references on maps or GIS positions.

The detailed information on known locations of populations of alien ornamental fish is provided in Table 2.1 Four additional ornamental fish species not included in the review list were included in this mapping survey. These are the pearl cichlid, firemouth cichlid, green terror and banded cichlid (Table 2.1). The distributions of all these species, based on the current data collected, are shown in Figures 2.1-2.27. The only ornamental species known to be present in the wild (Table 1.1), but for which no distributional data could be found, were the blue tilapia (*Oreochromis aureus*), the redhead cichlid (*Vieja synspila*) and the Sumatra barb (*Puntius tetrazona*). An as yet unidentified cichlid (either Mozambique tilapia, pearl cichlid or Jack Dempsey) has been reported from two artificial lakes in Perth (pers. comm. K. McNamara, Department of Environment & Conservation, Perth).

Table 2.1: Summary of the known locations of ornamental fish established in Australian waters in 2006.

Scientific name	Common name	Locations found in Australia	Information source
1. Hybrid cichlid	*Labeotropheus/Pseudotropheus*	Hazelwood power station (Vic)	ASFB (2001)
2. Jewel cichlid	*Hemichromis bimaculatus*	Rapid Creek in Darwin (NT); Ross River (northern Qld)	ASFB (2003b); A. Webb (pers. comm.); D. Wilson (pers. comm.)
3. Victoria Burton's haplochromis	*Haplochromis burtoni*	Ross River in northern Qld & Hinze Dam (south-east Qld)	Arthington et al. (1999); ASFB (2003b); A. Webb (pers. comm.)
4. Black mangrove cichlid	*Tilapia mariae*	Cairns area, Barron, Ross, Johnstone, Burdekin, Mulgrave and Russel Rivers (Qld); Hazelwood power station, Eel Hole Creek., Latrobe River (Vic.); Lake Burley Griffin Canberra (ACT)	Cadwallader et al. (1980); Arthington et al. (1999); McKenzie et al. (2000); ASFB (2001); Allen et al. (2002); ASFB (2003b), ASFB (2004b); A. Webb (pers. comm.)
5. Redbelly tilapia	*Tilapia zillii*	Chapman River near Geraldton (WA)	Arthington et al. (1999)
6. Blue tilapia	*Oreochromis aureus*	No data obtained	
7. Mozambique tilapia	*Oreochromis mossambicus*	Brisbane dams, Boyne River including Boondooma Dam, tidal Creeks around Townsville, Cairns, Atherton Tableland, Endeavour R. & Port Douglas; Barron, Ross, Mulgrave & North & South Johnstone and Pine Rivers, (Qld); Gascoyne, Lyons, Milnilya & Chapman Rivers in the Pilbara Drainage & limestone caves Exmouth (WA)	Arthington et al. (1984); Arthington & Milton (1986); Bludhorn & Arthington (1990b); DPIQ (2000); Allen et al. (2002); Low (2002); AFSB (2003b); ASFB (2003c); Lintermans (2004); Morgan et al. (2004); A. Webb (pers. comm.);
8. Oscar	*Astronotus ocellatus*	Ross River & creeks around Cairns (northern Qld)	Arthington et al. (1999); ASFB (2003b); A. Webb (pers. comm.)
9. Three-spot cichlid	*Cichlasoma trimaculatum*	Hinze Dam (south-east Qld)	Arthington et al. (1999)
10. Jack Dempsey	*Cichlasoma octofasciatum*	Angourie (northern NSW)	M. Lintermans (pers. comm.)
11. Firemouth cichlid	*Thorichthys meeki*	Ross River (northern Qld)	Arthington et al. (1999); ASFB (2003b); A. Webb (pers. comm.)
12. Banded cichlid	*Heros severus*	Ross River (northern Qld)	Arthington et al. (1999); ASFB (2003b); A. Webb (pers. comm.)

13. Redhead cichlid	*Vieja synspila*	No data obtained	
14. Red devil	*Amphilophus labiatus*	Ross River (northern Qld); & Hinze Dam (south-east Qld); Hazelwood pondage, LaTrobe Valley (Vic)	Arthington et al. (1999); ASFB (2001); A. Webb (pers. comm.)
15. Midas cichlid	*Amphilophus citrinellus*	Ross River (northern Qld)	ASFB (2003b); A. Webb (pers. comm.); M. Lintermans (pers. comm.)
16. Convict cichlid	*Archocentrus nigrofasciatus*	Ross River & streams around Townsville (northern Qld); Hazelwood power station, Eel Hole Creek, LaTrobe River (Vic.)	Cadwallader et al. (1980); Arthington et al. (1999); ASFB (2001); Allen et al. (2002); ASFB (2003b)
17. Blue acara	*Aequidens pulcher*	Creeks in Brisbane & Leslie Dam (south-east Qld); Hazelwood power station (Vic)	Arthington et al. (1999); ASFB (2001)
18. Green terror	*Aequidens rivulatus*	Ross River (northern Qld)	Arthington et al. (1999); ASFB (2003b); A. Webb (pers. comm.)
19. Pearl cichlid	*Geophagus brasiliensis*	Quarry & ornamental pool at Rockhampton & Bajool (Qld)	Arthington et al. (1999)
20. Green swordtail	*Xiphophorus hellerii*	Streams and rivers around Brisbane, Gladstone, between Maryborough & Cairns, Barron & Ross Rivers (northern Qld); Lake Ainsworth near Lennox Head & Burringbar Creek northern NSW (NSW); town Billabong in Nhulunbuy, dam at Alice Springs & Gunn Point and waters in the vicinity of Darwin (NT); Irwin River (WA).	Arthington et al. (1983); Morgan & Gill (2001); Allen et al. (2002); ASFB (2003a); ASFB (2003b); Morgan et al. (2004); A. Webb (pers. comm.); A. Moore (unpublished data); D. Wilson (pers.comm.), Northern Land Council (www.nlc.org.au).
21. Platy	*Xiphophorus maculatus*	Streams, swamps & drains around Brisbane, Calliope, Burrum Ross, Barron, Russell, Mulgrave, Tully, Johnstone & Babinda Rivers & Behana, Peewee, Louisa & Harley Creeks (northern Qld); town billabong in Nhulunbuy & Rapid Creek Darwin (NT).	Arthington et al. (1983); Arthington et al. (1999); Allen et al. (2002); ASFB (2003b); D. Wilson (pers.comm.); A. Webb (pers. comm.).
22. Sailfin molly	*Poecilia latipinna*	Streams and rivers around Brisbane & Harvey Bay, Ross River (northern Qld), waters in the vicinity of Darwin (NT).	Arthington et al. (1983); Arthington et al. (1999); Allen et al. (2002); ASFB (2003b); M. Lintermans (pers. comm.)

			Northern Land Council (www.nlc.org.au).
23. Guppy	*Poecilia reticulata*	Coastal drainages of Qld from Cairns to Brisbane, including the Burnett, Black Alice, Ross, Herbert, Fitzroy, Barron, Murray, Mossman, Mulgrave, Moresby & North & South Johnstone Rivers, Alligator & Crystal Creeks, Gustav Creek Magnetic Island, ponds & streams in Charters Towers (Qld); Billabong in Nhulunbuy, Railway Dam, Leanyer Swamp & Sadgroves Creek Darwin (NT); Roadside pool in Pilbara Drainage (WA).	Arthington et al. (1983); Arthington et al. (1999); Allen et al. (2002); ASFB (2003a); Morgan et al. (2004); A. Webb (pers. comm.); D. Wilson (pers.comm.).
24. Caudo	*Phalloceros caudimaculatus*	Swamps & drains around Perth, Swan-Avon Rivers; Canning River (WA).	Arthington et al. (1999); Allen et al. (2002); ASFB (2003a); Morgan et al. (2004); Rowley et al. (2005)
25. Three-spot gourami	*Trichogaster trichopterus*	Ross River & lower floodplain of the Burdekin River, Sheepstation Creek (northern Qld)	Arthington et al. (1999); ASFB (2003b); A. Webb (pers. comm.)
26. Oriental weatherloach	*Misgurnus anguillicaudatus*	Hazelwood power station, LaTrobe catchment & Yarra, Maribyrnong, Patterson, Campaspe, Don, Ovens & Murray Rivers, Corhanwarrabul, Nine Mile, Broken, Koonung, Ruffey & Dandenong Creeks (Vic); Mountain Creek Murrumbidgee catchment, Murrumbidgee, Murray, Wingecarribee, Queanbeyan, Peak, Wollondilly, Cox's Edwards, Neimur, Hawkesbury-Nepean Rivers & Lake Eucumbene, Tuppal Creek (NSW); Common in lowland streams including the lower Cotter, Paddy, Molonglo, Gudgenby, Queanbeyan and Ginninderra Creek, Gooromon Pondage, Halls, Tuggeranong Creeks, Lake Burley Griffin (ACT)	Allen (1984); Arthington et al. (1999); ASFB (2001); Koster et al. (2002); ACT (2002); ASFB (2003a); M. Lintermans (pers. comm.).

27. Goldfish	*Carassius auratus*	Fitzroy, Dawson & Burnett Rivers in northern Qld to NSW including most coastal & inland waters of NSW, Vic. & southern Qld; Coastal drainages of south western WA between Moore, Vasse & Blackwood Rivers, Canegrass Swamp & Bromus Dam (WA); common in lowland streams (ACT); Western Plateau of SA & Coopers Creek Lake Eyre drainage (SA)	Arthington et al. (1999); Allen et al. (2002); Morgan et al. (2004); M. Lintermans (pers. comm.)
28. Rosy barb	*Puntius conchonius*	Streams in and south of Brisbane (Qld); Margaret River area Western Australia	Allen et al. (2002); Arthington et al. (1999); ASFB (2006)
29. Sumatra barb	*Puntius tetrazona*	No data obtained	
30. White cloud mountain minnow	*Tanichthys albonubes*	Creek in Brisbane (Qld); Green Point Creek Central Coast, Piles Creek, Somersby (NSW)	ASFB (2003b); ASFB (2003c)

2.3 Maps of species distributions

Figure 2.1: Distribution of hybrid cichlid (*Labeotropheus/Pseudotropheus* cross).

Figure 2.2: Distribution of jewel cichlid (*Hemichromis bimaculatus*).

Figure 2.3: Distribution of Victoria Burton's haplochromis (*Haplochromis burtoni*).

Figure 2.4: Distribution of black mangrove cichlid (*Tilapia mariae*).

Figure 2.5: Distribution of redbelly tilapia (*Tilapia zillii*).

Figure 2.6: Distribution of mozambique tilapia (*Oreochromis mossambicus*).

Figure 2.7: Distribution of oscar (*Astronotus ocellatus*).

Figure 2.8: Distribution of three-spot cichlid (*Cichlasoma trimaculatum*).

Figure 2.9: Distribution of Jack Dempsey (*Cichlasoma octofasciatum*).

Figure 2.10: Distribution of firemouth cichlid *(Thorichthys meeki).*

Figure 2.11: Distribution of banded cichlid (*Heros severus*).

Figure 2.12: Distribution of red devil (*Amphilophus labiatus*).

Figure 2.13: Distribution of midas cichlid (*Amphilophus citrinellus*).

Figure 2.14: Distribution of convict cichlid (*Archocentrus nigrofasciatus*).

Figure 2.15: Distribution of blue acara (*Aequidens pulcher*).

Figure 2.16: Distribution of green terror (*Aequidens rivulatus*).

Figure 2.17: Distribution of pearl cichlid (*Geophagus brasiliensis*).

Figure 2.18: Distribution of green swordtail (*Xiphophorus hellerii*).

Figure 2.19: Distribution of platy (*Xiphophorus maculatus*).

Figure 2.20: Distribution of sailfin molly (*Poecilia latipinna*).

Figure 2.21: Distribution of guppy (*Poecilia reticulata*).

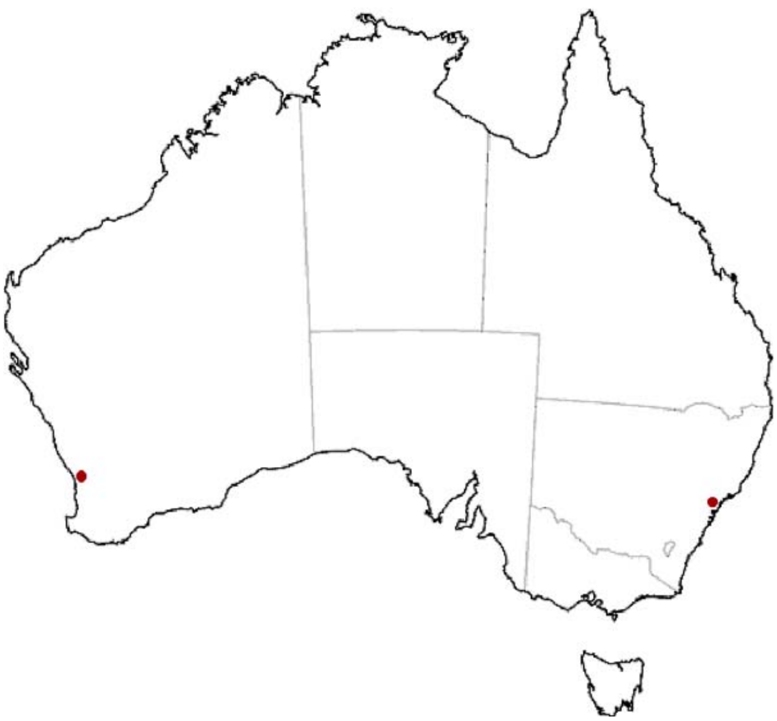

Figure 2.22: Distribution of caudo (*Phalloceros caudimaculatus*). The population in Sydney has now been eradicated (pers. comm. R Toffolon, NSW DPI).

Figure 2.23: Distribution of three-spot gourami (*Trichogaster trichopterus*).

Figure 2.24: Distribution of oriental weatherloach (*Misgurnus anguillicaudatus*).

Figure 2.25: Distribution of goldfish (*Carassius auratus*)**.**

Figure 2.26: Distribution of rosy barb (*Puntius conchonius*).

Figure 2.27: Distribution of white cloud mountain minnow (*Tanichthys albonubes*).

2.4 Distribution patterns and their implications

Queensland contains the highest number of established ornamental species including six species that have not been reported from there before (i.e. midas cichlid, oscar, three-spot cichlid, Victoria Burton's haplochromis, three-spot gourami and rosy barb. Only five out of the 23 listed species have not been reported from Queensland so far (i.e. redbelly tilapia, Jack Dempsey, *Labeotropheus/Pseudotropheus* cross cichlid, oriental weatherloach, one-spot live bearer). By contrast, the only listed ornamental species reported from Tasmania is the goldfish.

These latitudinal differences in ornamental fish distribution in the wild are not unexpected given that many of the listed species are tropical, warm-water fish. However, the preponderance of ornamental species in Queensland is not reflected in the Northern Territory or in the northern region of Western Australia. This may reflect the low potential for introduction of alien fish in more remote (northwestern) areas, but it may also reflect the paucity of fish surveys in these regions

Goldfish occur across the largest area of Australia (Fig. 2.25). Not only is this species present in six out of the eight States and Territories but it occurs in many waters throughout the entire south-eastern region of Australia. No record was reported for the northern half of the continent.

Mozambique tilapia (Fig. 2.6), guppy (Fig. 2.21) and platy (Fig. 2.19) are present over large geographic areas but these areas are confined to coastal regions.

Of the species, apart from goldfish that are typically found in temperate regions, oriental weatherloach was the most widespread in Australia in terms of its reported distribution (Fig. 2.24). Populations are now present in large areas of southern NSW, ACT and Victoria. One population of the white cloud mountain minnow was reported from Brisbane and another occurs further south (Fig. 2.27).

There are a number of species that, despite occurring within discrete locations, have been reported from a wide latitudinal range. These include red devil (Fig. 2.12), convict cichlid (Fig. 2.14), black mangrove cichlid (Fig. 2.4), Victoria Burton's haplochromis (Fig. 2.3), blue acara (Fig. 2.15), sailfin molly (Fig. 2.20) and green swordtail (Fig. 2.18). These species all have established populations in both the tropics and temperate regions of Australia. These findings belie the temperature ranges in which many of these species occur within their native range, indicating that matching environmental tolerances with climate (i.e. bioclimatic matching) is not always a reliable way of predicting the potential distribution of these species.

Species with a restricted latitudinal range but with a wide longitudinal range include the one spot live bearer (Fig. 2.22) and jewel cichlid (Fig. 2.2).

The remaining species have been reported only from a few restricted locations at present. They include midas cichlid (Fig. 2.13), oscar (Fig. 2.7), red belly tilapia (Fig. 2.5), three spot cichlid (Fig. 2.8), Jack Dempsey cichlid (Fig. 2.9), hybrid cichlid (Fig. 2.1), three spot gourami (Fig. 2.23), rosy barb (Fig. 2.26), firemouth cichlid (Fig. 2.10), pearl cichlid (Fig. 2.17), green terror (Fig. 2.16) and banded cichlid (Fig. 2.11).

It is clear that there is strong human involvement in the manner in which ornamental fish are dispersed in Australia (Lintermans 2004) and the distributional data presented here reinforce this. Liberations of alien fish are often concentrated around metropolitan areas because these are areas where the fish are kept in aquaria or ponds and local waters are more readily accessible than distant ones. By contrast, the spread of such species to more remote areas is typically limited (Arthington et al. 1999; Kailola 2000; Bomford and Glover 2004), mainly because of the cost and inconvenience of transporting them there. Human vectors can explain much of the clustering of these species close to major urban centres in Australia. For example, 16 species of ornamental fish are known to be established near Townsville, ten near Brisbane, five near Cairns, four near Darwin, three near Canberra, and three near Sydney (Figure 2.28).

No clusters of the ornamental species occurred away from major urban centres. This may reflect sampling coverage as more sampling is typically carried out close to such centres than far away from them. The proximity of the clusters in Figure 2.28 to major urban centres indicates that human dispersal is the major factor in the spread and establishment of these species and that public education is needed to counter this.

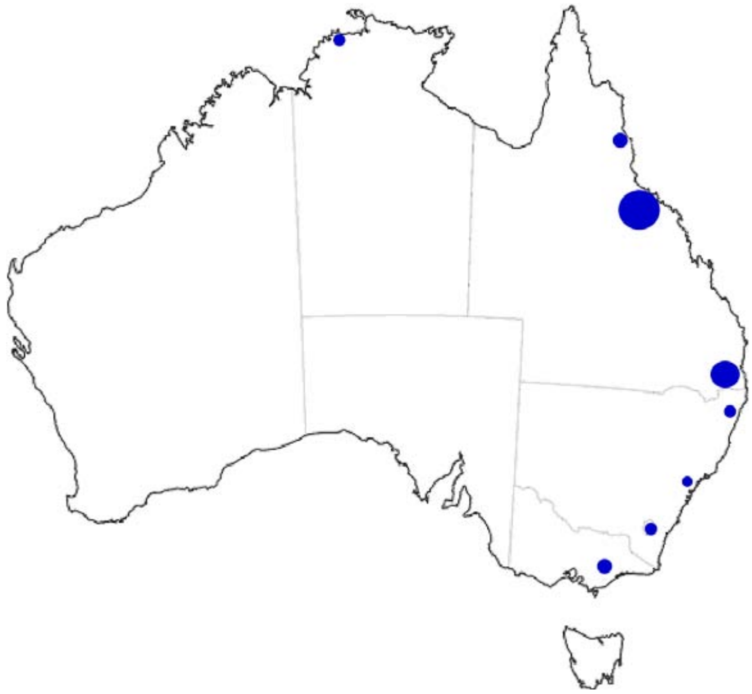

Figure 2.28: Locations where large numbers of ornamental fish species have become established in Australia. (The size of the circles reflects the number of species known to be established and ranges from three in Sydney to 16 in Townsville).

More successful incursions of ornamental fish would be expected near the warmer, northern cities of Darwin, Cairns, Townsville and Brisbane, than near southern cities because 'tropical' ornamental fish can be expected to be more successful at surviving and breeding in the warmer waters of the north. This is borne out by the data in Figure 2.28. However, the presence of 16 species near Townsville compared with only five in Cairns and no clusters in Mackay or Rockhampton was unexpected. This is likely to reflect either a bias in sampling coverage (i.e. proximity to James Cook University), or a more active trade for aquarium and pond species in Townsville than in other northern centres.

The absence of species clusters near Perth, Adelaide, Melbourne and Hobart may reflect their more southern location and the failure of ornamental species to establish in colder waters, but it may also reflect a lack of sampling and/or a reduced interest in ornamental species in these centres. Arthington et al (1990) noted the prevalence of alien fish species in more modified habitats, however, a scarcity of modified waterways is unlikely to account for the absence of ornamental alien species near these centres.

Although a warmer climate and human vectors can account for much of the overall distribution pattern for the clusters of ornamental fish species in Australia, the presence of a cluster of five species in western Victoria was associated with the thermal discharge from a power station (Arthington et al. 1999). This tends to support the view that although many ornamental species may have been released into natural waters close to major urban centres, their establishment has probably been constrained by a lack of suitable habitat (i.e. warm waters) in many southern regions.

2.5 Future distribution mapping

Overall, the distributional data on the established populations of ornamental fish suggests that the risk of these species becoming established is greater in the north where water temperatures are warmer than in the south. However, some warm-water species have become established in temperate as well as tropical regions. If the main environmental tolerances for the 23 ornamental species were known it would be theoretically possible to match these with environmental conditions and to develop maps of the potential spread of each species throughout Australia. Koehn (2004) carried out such a prediction for common carp using CSIRO's CLIMEX model. This model is based on air temperature data collected from monitoring stations throughout Australia and data on the thermal tolerance range for target alien species[2]. While the projected distribution map for the distribution of common carp was patchy because of the lack of coverage of air monitoring stations in Australia, the outputs of CLIMEX were useful in that they suggested that this species was capable of surviving in most parts of Australia. However, Koehn (2004) noted that a better solution would be to use a similar model based on water temperatures rather than air temperatures. In reality, this approach is probably impractical for many of the ornamental species found in Australia because their key environmental tolerances are not well known and corresponding data on the aquatic environment are also sparse. Furthermore, the temperature range occupied by a species in its natural range may not indicate its physiological tolerance and may reflect other factors such as the effects on its distribution of predation and competition by other species or physical habitat constraints. Maps of the predicted geographical distributions of the species studied here have been prepared using the known data on temperature tolerances (Bomford & Glover 2004). These provide a guide to potential distribution, but those species that can hybridise with other species may produce viable progeny with wider tolerances (c.f., Arthington 1991, Mather & Arthington 1991). Over time, strains of introduced species may become more tolerant of a wider range of environmental conditions.

A further complication to predicting fish distributions from environmental tolerances is provided by the occurrence of barriers to fish movement. These may restrict their spread despite the presence of suitable habitat up or downstream. Barriers not only include physical impediments to upstream movement such as culverts, falls and dams, but reaches with higher water velocities that may be impassable to species that are either small or have a poor swimming ability. Similarly, higher salinity reaches connecting freshwater streams may prevent the spread of species with low salinity tolerances. For these reasons, environmental-tolerance based predictions of the potential spread of ornamental fish species is likely to be of limited value and other

[2] CLIMEX has been used for predicting Cane Toad distributions in Australia (Koehn, 2004).

methods need to be developed to map fish distributions and to determine the potential spread of alien fish species.

Of these methods, the creation of a fish database is likely to prove the most useful in the long term. The United States Geological Survey (USGS) maintains an interactive database portraying the distribution of non-native, alien fish in the United States (http://nas.er.usgs.gov/queries/default.asp). It can be interrogated to provide information on alien fish reports and distributions for single or multiple species at scales ranging from watersheds upwards. It also provides an 'Alert' system which flags the location of recent new incursions of alien species and so provides a nationwide overall coordination of issues related to alien species. Such a centralised database is an essential tool for managing alien species.

In New Zealand, the National Institute for Water and Atmospheric Research (NIWA) owns and manages a freshwater fish database. This is described in Richardson (2005) and has proved highly effective for mapping the geographic distributions of fish and more latterly for generating models that predict species distributions based on habitat variables (Leathwick et al. 2005). This database was set up over two decades ago and now contains over 26,700 records. It is publically accessible, can be added to or interrogated easily by external organisations such as other government agencies or consultants and individual records can be examined to obtain data on other species present and habitat variables at each site. It is now linked to GIS layers providing data on the geology, topography and flow regime of sites where fish are recorded from.

A similar national database owned and maintained by a central federal agency in Australia such as DEWHA would be an extremely useful tool for collating records of fish distributions and therefore for monitoring the spread of established alien fish species in Australian waterways. This would facilitate the prioritisation of research, monitoring, control and eradication of such species and it would provide national coordination to ensure that control programmes in one state are not compromised by a lack of action in another region or state.

The Australian and New Guinea Fish Association (ANGFA) currently maintains such a national database for Australia. It covers a wide range of Australian fish species, including marine and freshwater as well as alien species. It provides a listing of the recorded locations for species and these can be examined to determine basic environmental data. It therefore has a structure, like the NIWA database, which allows the recording of key environmental data on sites where species are found and in this sense is best suited for a national database for research and monitoring purposes. However, it currently contains relatively few records.

The New South Wales Department of Primary Industry also has a freshwater fish database and access to some parts of this can be publically accessed via the BIONET website (www.bionet.nsw.gov.au). The mapping facilities in BIONET are much superior to those in the ANGFA database and there are many more records in BIONET. But it is limited to New South Wales and provides limited information on the environmental variables at sites where fish occur.

The Queensland Department of Primary Industries and Fisheries (QDPI&F) uses a GIS based database and mapping programme called PESTINFO as part of its alien fish management strategy (pers. comm., Mr T Chen, QDPI). The use of PESTINFO as a database for pest fish distribution data was suggested by Mackenzie (2003) as part of Queensland strategy for controlling and managing pest fish species in the state. Data are supplied to QDPI&F by regional management groups (essentially catchment management organisations). Data include the types of pest fish species, the GPS position where they are found, habitat information and the name of the property owner if found on private property. No biological or taxonomic specialist advice is incorporated into quality assurance of these data before entry into the database, so some identifications may be suspect and the robustness of the data may be questionable in certain cases. Regional management organisations are, however, given good keys for identifying pest fish species and should be able to readily identify pest species rated as high priority. One limitation of this arrangement is that species that are more difficult to identify or those that have only recently been introduced might be confused with other species or overlooked altogether. A further limitation on the use or access to this information is that regional management groups supplying the data have a copyright on the information, mainly to protect local councils and private property owners from problems. This copyright regulation prevents information being disclosed to third parties, and this may limit its usefulness for research to determine the ecology of established ornamental species.

The QDPI&F also have a monitoring system for assessing changes in the distribution of pest fish species in Queensland. This is the Annual Pest Fish Distribution Survey. Inland regions of the state are divided up into 50 x 50 km grids, while the coastal regions are divided up into 18 x 18 km grids. Before monitoring takes place, each grid square is evaluated in terms of the type of pest species already present, their priority rating (class 1 through to 3) and their density. This information is drawn together by members of each regional management group and fisheries scientists. A fish taxonomy /ecology specialist is also available to assess the information gained for its validity. Through this procedure, QDPI&F can develop targeted research and monitoring, as well as control and eradication programs. Distribution data collected through this processes is held by QDPI&F, though it is not clear whether it is also incorporated into the PestInfo database. The data are copyrighted by QDPI&F, so are available for use by outside organisations or individuals at their discretion. Information from this database was not used in our distribution mapping because of budgetary and IP constraints, but can be expected to provide a finer-scale indication of the distribution of ornamental fish species in Queensland.

There are several experts specialising in freshwater fish biology and invasive fish biology in Australia who also hold their own fish databases (viz. Alan Webb at James Cook University, Brad Pusey and Angela Arthington at Griffith University, Peter Davies at the University of Tasmania). There are probably other researchers who hold similar fish distribution databases in other parts of Australia, probably filling a gap not currently addressed by state and federal agencies. Clearly, there is an urgent need to pool such data in a nationally coordinated and publically funded database that is open to the public as well as to researchers.

If a centralised alien fish distribution database was to be adopted in Australia, state agencies would need to buy into the process and see it as a useful tool as well a key component of their management and decision-making procedures relating to freshwater fish management. They are likely to be both the major contributors as well as the main beneficiaries of such a system. At present, a number of useful fish database frameworks exist in Australia but none are nationally recognised or universally supported. This proliferation of databases will inhibit the development of a nationwide, authoritative record of freshwater fish distribution and hence the future development of fish distribution and habitat models needed by fish and water management agencies.

2.6 Recommendations

1. Confirm identifications of species over which there is confusion (e.g., hybrid cross cichlid, oriental weatherloach) and ensure that robust keys are available to aid the identification of ornamental fish species in the field.

2. Confirm the presence in the wild for the species reported to be present but for which no geographic data could be obtained.

3. Confirm the presence of breeding populations for species with very limited distributions and assess their risk of spread.

4. Investigate the feasibility of establishing a ‘national’ database for recording the distribution and spread of freshwater native and alien fish in Australia.

5. Investigate the reasons for incursion ‘hot spots’ in northern Queensland and, if required, develop targeted public relations campaigns to counter species’ introductions. This study would need to address the relationship between propagule pressure and introduction pathways along with other potential causes of such hot-spots.

6. Identify the isolated species incursion for those species that may pose a threat if they spread and rapidly determine the feasibility of their eradication to prevent further spread.

3. Review of impact assessment methodologies

3.1 Introduction

Opinions vary about the extent and nature of impacts of alien fish species on the environment in Australia. The establishment of some alien fish (e.g., trout) is seen by many as beneficial whereas the establishment of other species (e.g., common carp) is regarded as detrimental. Such generalisations are value judgments rather than scientific assessments (Rosenweig 2001; Slobodkin 2001 cited in Lodge and Shrader-Frechette 2003) and a number of fish ecologists have recently expressed concern over the potential for some, but not all, alien fish to cause ecological problems in Australia. These ecologists provide a more objective view of impacts and advocate the use of a scientific approach rather than value judgements to test their concerns and to provide objective information on the potential for impacts to occur in the wild.

The need for valid information on impacts is especially important for ornamental fish species in Australia because a number of these species are now established in the wild (see chapter 2) and blanket control would be economically unsustainable and not required in many cases. Furthermore, differences in perceived impact arising from a lack of information may result in conflict between opposing stakeholder groups and increase pressure on government and resource management agencies to develop effective policy and actions. However, it is difficult to deliver effective policy and management where the facts are unclear and any management attempts to prioritise control and eradication actions for certain species will be undermined if there is little objective information on impacts, or if the potential benefits of proposed control measures are unknown (Bomford and Tilzey 1996).

Uncertainty about the impacts of ornamental fish species could also lead to resistance by stakeholders to contribute to the management of the issues. Unless there is good evidence of potential impacts and information on their extent, stakeholder groups may feel no obligation to contribute to or assist with the process of resolving any environmental issues.

Assessments of the impacts of established ornamental species are also needed to provide information for risk assessments addressing the importation of other ornamental fish into Australia. For example, Coates and Ulaiwi (1995) attempted this when ground-truthing their alien fish introduction risk assessment model for Papua New Guinea. Although such hind-casting approaches do not allow prediction of all impacts, they can validate or invalidate criteria used as part of other existing frameworks. This, in turn, will ensure that systems for assessing the risk of importation of ornamental fish species in Australia become more robust.

The literature on the risks of importation, introduction and establishment of alien fish species is littered with examples of authors who cite a lack of information on impacts.

Koehn and Mackenzie (2004) are among the most recent Australian authors to note this as a problem. As a result, strategies for managing established alien fish species in Australia are often based on predictions derived from risk assessment frameworks such as that developed by Arthington et al. (1999) and Bomford and Glover (2004). These usually rely on evidence of impacts from other countries and hence on potential impacts in Australia. For some species, predicted impacts are based on anecdotal evidence or on results from a limited number of studies. One of the problems with using this sort of generalised risk assessment is that it tends to either constitute a hind-casting exercise as when applied to well-established and well-studied species (such as carp, *Gambusia* and tilapia), or a best guess approach reliant on limited data that have not necessarily been critically assessed when applied to less well-studied species. It is the latter situation that is of most concern, because flawed predictions of impact can lead to either a lack of intervention where it is required, or to costs being incurred to tackle a resource management issue when it does not exist.

For the 23 species of established ornamental fish covered in this report it is important to determine the extent of knowledge concerning their impacts and to evaluate the reliability of the information available. Arthington and Mackenzie (1997) sum up the current situation succinctly:

'there is a desperate need for hard data rather than anecdote and speculation'.

Although further investigation of the impacts of established ornamental fish species in Australia is no doubt warranted, surety to all stakeholders can only be gained if those studies are robust and provide useful information. Reviewing past studies provided us with an opportunity to identify the lessons learned so that the objectives of new studies are properly set and met when future monitoring and research is carried out. There have been relatively few critical reviews of the evidence of impacts of alien fish in Australia. Weatherley and Lake (1967), Arthington (1991), Arthington and Blühdorn (1995), Arthington and Mackenzie (1997) and Clarke and Grosse (2000) examined the weight of evidence for impacts associated with several established alien fish species, but few of the 23 established ornamental species were considered by them. Furthermore, even though the evidence of impacts was reviewed, none of these studies examined the way in which the data were collected or how the findings were interpreted and reported.

As part of this study, we were asked to critically review the methodologies used to gather data on the impacts of alien fish. Identifying the strengths and limitations of different impact assessment methodologies is a necessary precursor to reviewing evidence of impact. It also helps identify the most appropriate methods and approaches for future studies. The methodological tools used to determine the impacts of alien species on natural ecosystems in Australia are therefore reviewed as a precursor to assessing the evidence for impacts of ornamental fish. This review includes an assessment of the ways in which evidence of the impacts of alien fish species are reported in the literature and it examines the 'levels of proof' required to establish acceptance of impacts. It also describes the main limitations that have been experienced in gathering evidence of impacts by the various methods and it provides guidance on the approaches and methods that can be used in the future to answer questions on the impact of ornamental fish introductions in Australia.

3.2 Establishing the 'burden of proof'

There are different types and levels of proof required in impact assessment and a knowledge of the 'burden of proof' (i.e. the type, amount and quality of information required by managers before they can accept that an impact is occurring and action is warranted) is rarely discussed in reviews of the impacts of alien fish species. Nevertheless, it is an important issue to acknowledge and understand before undertaking any attempt to assess the weight of evidence for or against impacts.

The burden of proof tends to vary with stakeholder perspective. For example, conservation groups may require a low level of proof of impact and advocate a precautionary approach to alien fish control principally because there is a lack of information and it is better to be 'safe than sorry'. Some researchers begin with the premise that it is rare for the introduction of alien fish to have no impacts and that few introductions of ornamental fish have resulted in benefits to humans or the environment (e.g., De Iongh and Van Zon 1993; Welcomme, 1984 and Moyle, 1985 cited in Arthington 1991). For example, the mere presence of a large population of alien fish implies additional pressure on some food resource, and by implication a reduction in this for native species. Such sentiments are based on the principle that all 'niches' are filled and that introduction of an alien species occupies a part of the niche once occupied by indigenous species. This is the ultimate in terms of a precautionary approach and it may lead to costly and unnecessary action if, in fact, there is no problem. Lodge and Shrader-Frechette (2003) suggest that we should avoid such simplistic approaches.

By contrast, the groups that have some responsibility for creating or managing the impact may require a much higher burden of proof based on peer-reviewed, scientifically-defensible, replicated studies. These can be costly, may take many years to complete and, in some cases, the results may not be clear-cut. Some balance is therefore required in terms of the level of proof of impact that is required before policy initiatives are refined and implemented to tackle the issue of feral ornamental fish.

Koehn (2004) argued for a balanced approach and indicated that it is better to assess the risk of invasive fish species based on qualitative information than to avoid considering risk at all, or to wait until semi-quantitative or quantitative data become available and provide a clearer indication of actual risk. Given the potential for lost opportunities to control alien fish at any point between introduction and establishment, this view is certainly valid and may help reduce the spread of some species. It is a common sense approach to be advocated when fish introductions are limited to few sites and the potential for spread can be readily halted (i.e. a site-led management approach). However, it may not be appropriate for species already well established in a wide range of locations and spreading. A more quantitative, wider-scale approach to impact assessment may be required to underpin the more expensive management required for these species (i.e. a species-led management approach). The level of proof required for acceptance of an impact can therefore vary depending on both stakeholder perspectives and the geographic distribution (and spread) of the introduced species (i.e. site- versus species-led approaches).

The level of proof is also important in terms of type I and type II errors associated with data analysis and reporting. When assessing the impacts of established ornamental fish, committing type II errors (failing to detect an impact when it is present) could mean that resource managers overlook impacts and only realise that they are occurring much later, when the consequences are manifested and it is too late for remediation. On the other hand, type I errors (identifying an impact when it is not present) could mean that money, time and resources are wasted on trying to remedy or mitigate impacts that are either non-existent or too trivial to be considered ecologically significant. The level of proof required clearly needs to avoid such traps, especially type II errors could be much more expensive to fix in the long term.

The level of proof also depends on the type and scale of impact assessment. Small-scale aquaria and tank-based experiments (microcosms) or experiments in enclosures, limnocorals and artificial ponds (mesocosms) may reveal an impact that only occurs when alien species are artificially constrained and this may not occur in the wild. Ling (2004) stated; " *Gambusia is an aggressive little fish and cannibalistic, and commonly displays significant aggression towards other species and each other when confined in laboratory aquaria. Inter-specific competition is often directed to adult fish much larger than themselves. Such studies are often given as evidence that Gambusia may wreak havoc on wild populations. What is unclear is how closely these confined aquarium experiments mimic impact in natural habitats or larger scale, natural experimental systems".* The level of proof of impact from such controlled experiments will clearly be less than that based on experiments using ponds or mesocosms let alone natural waters. In this respect, a high autumn mortality of *Galaxias gracilis* caused by fin-biting from *Gambusia* was recorded in a New Zealand lake indicating that tank observations of such behaviour can occur in the field (Rowe 2003).

Furthermore, the issue of the predictive power of impact assessments arises even when there is solid evidence of an impact in a natural environment. An impact from an alien fish species may be demonstrated to a high level of proof within one or two natural waters, but this does not necessarily mean that every wild population will produce a similar impact. Impacts in the wild may vary greatly depending on site and time-specific factors. For example, gambusia may not have an impact on native fish in some lakes because the area of shallow littoral zone, where interactions occur, is small or not important for the other fish. Similarly, effects of gambusia on native fish in rivers may not occur until severe droughts or heavy abstractions reduce river flows, concentrating fish species within shallow pools. Ideally, impacts need to be scientifically demonstrated at a range of scales as well as over a wide geographic area before species-led control programmes are adopted. The level of proof required to demonstrate an impact therefore depends on the scale of the assessment experiment as well as on the generalisation of such results across a wider geographic region.

Because the level of proof required to demonstrate an impact depends on many factors and can vary greatly, it can provide a stumbling block for managers and become a major issue between opposing stakeholder groups. Furthermore, economic factors may need to be considered by managers alongside proof of ecological impact before establishing control programmes. The 'burden of proof' of impact can thus depend as much on socio-economic factors as it does on scientific ones. Because of this, a mutually-agreed consensus view from all key stakeholders, or a majority agreement among them as to what level of proof is acceptable, may be required. This recognises the fact that management decisions may be needed urgently and cannot always be based entirely on unequivocal scientific evidence. Reaching such agreements might be difficult. However, the ornamental fish industry will probably want a relatively high degree of proof of impact, particularly if the consequences of not having this proof will mean tighter regulations and negative publicity, or if funds are sought from the industry for investigations of perceived issues. By contrast, conservation groups are likely to opt for a much lower level of proof more in keeping with the precautionary principal. Ultimately, the 'burden of proof' required to trigger management action needs to be guided by both scientific principles and socio-economic considerations and determined *a priori* to avoid disputes.

3.3 Approaches to impact assessment

The review of the impact of alien fish in Australia indicated that most studies can be broadly categorised into one of five major approaches which vary in the level of proof of impact provided. These are, from the lowest to highest level of information provided: (a) the existence of a breeding population of an introduced species in the wild, (b) a risk assessment approach based on one or more of niche theory, population dynamics and a history of invasiveness or pest status elsewhere, (c) a correlative or epidemiological approach based on the repeated observation of cause and effect patterns across both temporal and geographic scales, (d) a mechanistic approach based on the identification and experimental verification of all the causal links between and introduced species and its impacts, and (e) a triple bottom-line approach wherein ecological impacts are evaluated alongside social and economic ones.

3.4 Presence of a breeding population

The establishment of an alien fish population in a natural waterway can be regarded as an impact in its own right on the basis that it represents a deviation from naturalness (Kennard et al. 2005). Although the introduction of a new fish species may not have a detectable effect on the native fauna and flora or natural habitats, the existence of such a fish population requires resources for its production. In some cases, these will be drawn from sources formerly utilised by native species and in this sense the introduction has resulted in an impact. However, the salient point is that it has not affected the natural ecosystem values considered important by society. Nonetheless, Arthington and Blühdorn (1995) are right in saying:

"All the established exotic fish species have one negative economic impact represented by the resources required to monitor, investigate, manage and, in a few isolated cases, exterminate them."

Pollard and Burchmore (1986) in their hypothetical outlook for what Australia's fish fauna might look like in 2000, reflected on the fact that their grandchildren would find a different fauna to that they had seen and experienced. In this context, the introduction of an alien fish has changed the fish fauna from its natural state and in the eyes of these authors this constitutes an impact because it limits future knowledge and experience of natural aquatic ecosystems for future generations.

Some indigenous peoples in Australia regard the concept of naturalness as a fluid one, whereby the flora, fauna or ecological processes prevailing at any given time are what is natural. This view accepts that native fish communities will eventually be supplanted by alien species, but the extent to which this view is widespread or held by a majority of Australians is unknown. For some, the establishment of certain alien species in some waters may be acceptable. For example, in their statement, *"I suppose we had to be grateful that at least some fish could still live in the more polluted of our rivers"* Pollard and Burchmore (1986) accept that alien fish may be the only species that can survive in some highly degraded environments. In this sense, they fill a 'vacant niche', albeit a man-made rather than a natural one. Some may believe that invasions of new habitats may compensate for the extirpation pressures some species face in their natural habitat. For example, Botkin (2001) stated that: *"…biological invasions are natural and, more important, necessary for the persistence of life."* Furthermore, Flannery (2001) stated that: *"extinctions and invasions of biota characterised the Earth long before humans existed"*. However, Gurevitch and Padilla (2004) stated that: "*Most ecologists would not…regard the establishment of five new widespread alien species in a region as 'biotic compensation' for the extinction of five endemics."* Views on the role of alien fish in 'new environments' or in 'unfilled niches' clearly differ and raise questions about how alien fish species might alter food webs and affect ecosystem stability and resilience. This more holistic approach to alien fish impacts awaits further development of knowledge about the importance of ecosystem stability and resilience for ecosystem functioning and sustainability before it can be applied to impact assessments.

Although deviation from naturalness may be taken by some as an impact, most biologists rarely refer to this when reporting their findings on a particular alien fish species. The implicit assumption is that it is not an impact that most of society is concerned with. However, this view is changing and incorporation of societal views on the issue of naturalness into future impact assessments may be required. Deviation from naturalness was addressed in relation to alien fish by Arthington (1991) and is increasingly being adopted as a basis for identifying the impacts of alien species. Even if the presence of a breeding population of fish, without further evidence of impact, was to become a major concern in its own right, some benchmarking of the importance placed on naturalness would need to be developed before it could be placed in a management, decision-making context.

3.5 Desk-top risk assessments

Another form of impact assessment occurs where authors use a combination of the maximum size of a fish species, its likely spatial distribution, history of invasiveness, known biological traits, reproductive potential and its pest status in other countries to determine the potential for impact. This 'risk assessment' approach is based on the application of knowledge of the species gained elsewhere to predict potential impacts at locations where it is not yet present but may become established. It is a precautionary approach, and has been likened to 'shooting first and asking questions later' (McDowall 2004). This approach can be justified when applied to potential new importations or to species with limited existing geographical ranges in Australia because with no or few wild populations it is difficult to establish whether such species will pose a problem for the Australian fauna. However, this approach is of limited value when applied to predicting the impacts of species already well established in the wild. The impacts of widely established species can be determined by more scientifically robust approaches.

Pollard and Burchmore (1986) attempted to predict the future spread and impacts associated with alien fish species in Australia. Their predictions were necessarily couched in hypothetical terms and were acknowledged as representing a 'worst-case' scenario, but they did take into account other sources of environmental stress. An Australian example of a precautionary approach in reporting is provided by Blühdorn and Arthington (1990a) for tilapia (*O. mossambicus* and *O. mariae*). They identified niche separation and partitioning in the water column between tilapia and two other large native species (*Tandanus tandanus* and *Leiopotherapon unicolor*) with respect to use of food resources and foraging patterns and stated that *"no hard evidence is yet available on adverse effects (of tilapia) on native fishes"*. Despite this lack of evidence for impacts in Australian waters, they recommended in their Management

Plan for Australia (with respect to tilapia) that all tilapiine species be declared noxious.

Some assessments of impact based on risk assessments assume that species judged likely to be good invaders will turn out to be pests. However, invasiveness and impacts are not always linked. For example, in an appraisal of the question "are invasive species a major cause of extinctions?" Gurevitch and Padilla (2004) stated that the *"link between species invasions and extinction of natives is widely accepted by scientists as well as conservationists, but available data supporting invasion as a cause of extinction are, in many cases, anecdotal, speculative and based upon limited observation"*. Invasiveness was originally applied to plants and terrestrial animals because of their rapid spread and damage to terrestrial ecosystems. It is an appropriate trait for defining the pest potential of species inhabiting terrestrial ecosystems, but is not necessarily a useful trait for defining the potential impacts of fish in aquatic ecosystems. The extent to which a fish can become a pest therefore needs to be based more on traits related to its impact on the native fauna or flora than on its invasive potential. The social and economic importance of any such impact will then be determined by its invasive potential.

Desk top assessments of the invasive potential of freshwater fish in Australia have been carried out by Arthington et al. (1999) and more recently by Bomford and Glover (2004). The former scored species on the basis of their previous success at invading other countries, their propagule pressure (a measure of total fish numbers imported and the probability of releases) and the extent of bioclimatic matching. The latter used a similar but greater number of scoring metrics (viz., climate match, overseas geographic range, history of establishment elsewhere, taxonomic group). Both assessments scored most of the ornamental fish species highly (i.e. high invasive potential) with the only marked differences occurring for Victoria Burton's haplochromis and the three spot cichlid (Table 3.1).

Other desk top assessments have addressed the risk of pathogen importation and spread to native fish (AQIS 1999) but not the invasiveness or potential ecological impacts of these species. Clarke et al. (2000) assessed the environmental threats of various introduced pests in Australia, including goldfish, guppy and Mozambique tilapia, but did not address invasiveness or disease risk.

Table 3.1 Ratings of the invasive potential of ornamental fish species present in the wild in Australia

Common name	Scientific name	Potential risk of invasion	
		Arthington et al. (1999) method	Bomford & Glover (2004) method
Hybrid cichlid	*Labeotropheus/Pseudotropheus*	----------	-----------
Jewel cichlid	*Hemichromis bimaculatus*	Very high	Very high
Victoria Burton's haplochromis	*Haplochromis burtoni*	Very high	Low
Black mangrove cichlid	*Tilapia mariae*	Very high	High
Redbelly tilapia	*Tilapia zillii*	Very high	Very high
Mozambique tilapia	*Oreochromis mossambicus*	Very high	Extreme
Oscar	*Astronotus ocellatus*	Very high	Very high
Three-spot cichlid	*Cichlasoma trimaculatum*	Very high	Moderate
Jack Dempsey	*Cichlasoma octofasciatum*	Very high	High
Red devil	*Amphilophus labiatus*	High	High
Midas cichlid	*Amphilophus citrinellus*	Very high	
Convict cichlid	*Archocentrus nigrofasciatus*		High
Blue acara	*Aequidens pulcher*	Very high	Moderate
Green swordtail	*Xiphophorus hellerii*	Very high	Very high
Platy	*Xiphophorus maculatus*	Very high	Very high
Sailfin molly	*Poecilia latipinna*	Very high	Very high
Guppy	*Poecilia reticulata*	Very high	Extreme
Caudo	*Phalloceros caudimaculatus*	Very high	High
Three-spot gourami	*Trichogaster trichopterus*	Very high	Extreme
Oriental weatherloach	*Misgurnus anguillicaudatus*	Very high	High
Goldfish	*Carassius auratus*	Very high	Extreme
Rosy barb	*Puntius conchonius*	High	Very high
White cloud mountain minnow	*Tanichthys albonubes*	Moderate-high	High

According to the report 'Strategic Approach to the Management of Ornamental Fish in Australia', published by the Department of Agriculture Fisheries & Forestry (DAFF) in 2005 (DAFF 2005), the assessment of pest status is carried out independently across state jurisdictions, with both Queensland and Victoria undertaking recent reviews of their lists. A national noxious species list is now being considered and the criteria used for ascribing noxiousness are being examined in greater detail. All jurisdictions now base their assessments of noxiousness on the degree to which an alien fish species can become a pest, and this can include aggressive behaviour, piscivorous diet, high fecundity, frequent spawning over a long life span, potential maximum size, broad habitat tolerances and morphological similarity to native species. The authors of the DAFF report felt that *"meeting one of these criteria alone was not sufficient to qualify a species as noxious; those species proposed for addition to a national list met many, if not all, of the criteria"*. We support this approach and it has clearly been adopted in various state jurisdictions for some species already registered as noxious but not yet present in Australia (e.g., Nile perch and walking catfish).

Risk assessment approaches are based largely on the informed judgement of experts in the field and most involve a ranking or scoring system for the various variables incorporated into them. So far we are unaware of any risk assessments that have used Bayesian probability to test or refine decision-making. This is where the main risk factors are identified by experts and are given a probability value reflecting their contribution to the overall risk based on the knowledge and experience of the experts rather than on an actual measurement. Bayesian models are ideally suited for risk assessments where the number of primary variables is large, there are important secondary variables that may influence these, and where it is difficult to measure all of the variables contributing to risk. Bayesian probability involves the assignation of a 'best guess' probability function to each level of interaction between the variables ultimately influencing the impact. A Bayesian model then integrates and combines these. The application of Bayesian probability to risk assessments should therefore be considered in the future.

Although risk assessments may be useful tools for screening species for importation, they are less useful in predicting impacts once a species becomes established in the wild. Because of this, they should be viewed as a means of developing hypotheses about potential impacts which can then be tested using other approaches.

3.6 Correlative approaches

Stronger proof of impact can be provided where similar impacts are recorded consistently and repeatedly across a number of sites and/or habitats (i.e. there is a strong correlation between the presence and/or density of an alien species and a given impact). It would be erroneous and costly to assume that only deterministic, experimentally-verified identification of the links between cause and effect provides proof that a problem exists. Correlative approaches have been successfully used to establish links between a cause and its effect without full knowledge of the mechanisms involved. For example, cigarette smoking has now been strongly linked to lung cancer through epidemiological studies which do not reveal the precise mechanism of impact. Furthermore, Lodge and Shrader-Frechette (2003) stated that:

"…one often cannot easily determine what caused a cancer in a given case, so one must resort either to an empirically determined dose-response curve or a probabilistic model. Yet this failure to attain knowledge of cancer causation provides no grounds for denying either that the cancer rate, statistically speaking has been increasing…"

The repetition of patterns across a large number of samples is often used as an alternative to establishing causal links in both medicine and the social sciences where the mechanisms of cause and effect are highly complex and affected by numerous extraneous factors. In clinical trials of a new drug, testing of applicability is often based on log-linear regression analysis of data from different patient treatment groups (Lodge and Shrader-Frechette 2003). Understanding the mechanisms involved in the success of particular drugs may then come after this.

In the USA, an example of the correlative approach to impact assessment involving fish was provided by Moyle et al. (1986). They suggested that the patterns they observed in relation to associations between carp, habitat parameters, native American fish communities and their prey were so widely repeated that explanations other than impacts of carp are unlikely.

Changes in the relative abundance of native species versus alien species, and/or changes in species composition are the easiest parameters to measure to provide evidence of an impact. Kennard et al. (2005) also developed indices of ecosystem health which included the ratio of native to alien species as well as the observed as against expected fish species composition for waterways in south east Queensland.

One of the more robust ways of testing impact hypotheses based on correlative data is the Before-After-Control-Impact (BACI), or beyond-BACI approach, with the proviso that an appropriate level of replication relative to background variation has been used (Underwood 1991). These experimental designs are now highly regarded in Australia and are cited in a variety of national guidelines, including the ANZECC guidelines (ANZECC/ARMCANZ 2000) and the National Ocean Dredge Spoil Disposal Management Guidelines (E.A. 2002).

A range of novel univariate and multivariate statistical techniques is also now being increasingly used to establish negative associations between alien fish and native species. Some can even provide an indication of the amount of variation in native species composition explained by alien fish after that attributed to other factors has been taken into account. Examples of these types of study are provided by Gilliam et al. (1993) and Godhino & Fereira (1998). The use of a variety of statistical approaches as part of a single study can provide multiple lines of evidence for assessing the impact of alien fish on native fish, even where that evidence is based purely on correlation.

One of the problems with the correlative approach is that the causal links between any decline in native species and the introduction of alien fish are not established. Whereas changes in native species may coincide with the distribution of alien fish or the timing of their release and, in some cases the differences may appear marked, the impacts of unmeasured factors coinciding with these events cannot be ruled out. An example of this is the impact of degraded water quality on native species and the documented numerical dominance of established alien species over native species in such habitats. Bunn & Arthington (2002) also noted that impacts related to alien fish may also correlate with changes in flow regulation. Although workers such as Kennard et al. (2005) have been able to establish that the correlation between alien fish and poor water quality makes established alien fish potentially good indicators of ecosystem health, no worker has been able to prove categorically whether the decline in native fish in such regions is driven by direct interactions with alien fish, by a decline in water quality attributed to the activities of alien fish, or to anthropogenic degradation of water quality (i.e. unrelated to the activities on alien fish). We nearly always lack the pre-introduction data to be able to answer such questions and are caught in a 'chicken or egg' style dilemma. Even where there is a clear pattern of mutually exclusive distribution of alien and native fish, such as that observed for *Gambusia holbrooki* and the oxleyan pigmy perch *Nannoperca oxleyana* in Australia (Lloyd 1987, Lloyd & Walker 1986), there remains the possibility that the observed patterns are a result of unmeasured factors or processes unrelated to the actions of the alien fish.

Such problems need to be overcome by the application of manipulation experiments in which the prime cause of an impact is either reduced or eliminated to see if the impact is reversed, and *vice versa*. Recent Australian examples of this approach are the removal of trout from small streams by firstly, the creation of artificial barriers to their upstream movement and secondly by the removal of upstream populations (e.g., Lintermans 2000; Jackson et al. 2004). These measures resulted in galaxiid recolonisation of waters formerly occupied by the trout. Such 'management' experiments provide strong evidence that trout were the main cause of galaxiid decline in that particular system, and hence that other factors were not affecting the galaxiids as much.

A further limitation associated with the correlation-based approach is associating a lack of detectable change with a lack of impact (e.g., Kushlan 1986). This ignores the possibility that either the experimental design was not sufficient to detect changes over and above background variability, or that impacts may have resulted in consequences that simply haven't been measured. In most of these cases, workers may have only measured relative abundance, or species composition of fish, whereas there may have been more subtle impacts such as reduced condition or size, or increased susceptibility to pathogens that went undetected, but which could manifest themselves as changes in relative abundance or species composition at some later date. Absence of proof is not proof of absence. Therefore, in circumstances where significant impacts are not detected and the species in question has no identifiable beneficial value, it might be best not to assume that its effects are ecologically benign (Lodge & Shrader-Frechette 2003).

3.7 Mechanistic approaches

A good understanding of the impact mechanisms of alien species can help resource managers both confirm a suspected cause and effect relationship as well as to identify the best methods of pest control or the mitigation of impacts. An understanding of impact processes is also essential for allowing resource managers to determine whether the impacts are acceptable or a major threat to the resources/values they are charged with protecting. For instance, managers can be expected to treat the mortality of a threatened species with far greater emphasis than a restriction in its range, a change in its distribution, or a shift in behaviour. Understanding mechanisms can also be useful in predicting the time it might take for impacts to become obvious as large-scale or serious long-term changes. Such information provides a timescale on which to base management responses to impacts. In ecological science, assembling all such pieces of information together is sometimes referred to as 'matching patterns with processes'. In Australia, there is increasing support for this approach to be used more in ecology and for ecologist to move away from looking at patterns for their own sake (Constable 1999; Fairweather 1999). A greater emphasis on processes, rather than on patterns, now needs to apply when assessing the impacts of established ornamental fish on Australia's waterways and native biota.

One common problem with measuring factors associated with impact mechanisms is the problem of scale. The demonstration of predation, competition and aggressive behaviour by alien fish toward native fish is often achieved only at the microcosm or mesocosm scale (Lodge et al. 1998; Ling 2004). Evidence often consists of visual observations repeated over time on a number of individuals**,** and occasionally, exclusion or manipulative experiments. Such experiments can provide insights into linkages between impact mechanisms and impact consequences and may aid in determining whether the impact mechanisms persist over a range of situations and life stages. For instance, researchers may wish to know whether fin-nipping behaviour exhibited by an alien fish towards a native fish occurs only during spawning or if food supply is limited, or whether it occurs regardless of such factors. They might also want to know what levels a shared resource must reach before competitive behaviour and/or exclusion becomes evident.

The results from micro- or mesocosm studies, or from artificial streams, are less easy to refute than findings based on correlation or association only, but their ability to adequately represent what might occur at larger scales under field conditions is often called into question (Ling 2004; Lodge et al. 1998). It is up to researchers to outline the limitations based on scale as clearly as possible when presenting their interpretation of the results. Replicating such experiments on 'large-scale, natural environments' may be theoretically possible (because of the presence of such environments), but it is rarely logistically possible because of either the financial cost or community or legislative resistance to manipulation of waterways on a larger scale for experimental purposes. As a result, evidence of impacts revealed in smaller-scale, micro- or mesocosms is often necessarily interpolated to larger spatial scales under natural conditions and the ground-truthing of this at larger scales under field conditions is not explored further due to the above constraints. Both are negative outcomes and workers in the field of alien fish research and their management should be encouraged to try and persuade funding bodies to understand why it is advisable to test laboratory-scale observations in the field wherever possible.

Even where the impacts of alien fish are linked to the extinction of a native species, it may not be enough to simply establish the causal links. The question of whether or not these impacts are (or are likely to be) the primary cause of extinction also needs to be addressed. Often, impacts of alien species are synergistic (additive) to those of other stressors. Gurevitch and Padilla (2004) stated: *"Exotic species might be a primary cause for decline, a contributing factor for a species already in trouble, the final nail in the coffin or merely a bouquet at the funeral."* Establishing the relative contribution of alien species to declines, extirpations or extinctions is a daunting task (Gurevitch & Padilla 2004) and closer examination of actual case histories is required to determine the role of alien species. Gathering such information will help resource managers decide whether the removal of ornamental fish will prevent extinctions or extirpations from occurring or whether their resources might be better served in mitigating the impacts of other stressors.

In addition to visual assessments of behaviour and manipulative and exclusion experiments, researchers often assess diet and predator-prey interactions when investigating the impact mechanisms and consequences of introduced fish (e.g., Arthington et al. 1990). Assessments of gut content can be used to either demonstrate overlapping trophic requirements, or to demonstrate that predation of native fish has occurred (and to what degree and also at what life stage). As dietary assessments relate to field conditions, they are of value for assessing actual and potential impacts on native fish. Where there are several co-occurring alien species, dietary analysis might indicate whether populations of some of those alien species are controlled by predation pressure from others (Ruiz et al. 1992). Such information could be critical, as targeting the predator species for control or eradication might result in a marked increase in the populations of the prey species. This, in turn, could result in unforeseen pressures on native species.

Apart from providing direct evidence of predation on native fish, diet studies can also provide information on potential inter-specific competition, particularly when the dietary preferences, feeding behaviour and feeding zones of both alien and native fish species are known to overlap. For example, there is good evidence that the diets of the ornate rainbow fish *Rhabdinocentrus ornatus* and *Gambusia holbrooki* overlap, at least intermittently (Arthington & Marshall 1999), so evidence of potential inter-specific competition between the two can be inferred. Note that evidence should still be sought that the dietary resources are in short supply before causality for any decline in *R. ornatus* can be assumed. At very least, inferences about abundance of prey items should be made based on visual observations or knowledge of the prey species' life history, as done by Arthington and Marshall (1999). Low dietary overlap might be interpreted as resource partitioning as a result of past competition (Connell 1980 cited in Arthington & Marshall 1999). Thus, observations of the degree of dietary overlap may need to be repeated over a range of sites and times before inter-specific competition can be eliminated as a potential contributor to low dietary overlap.

Weatherley & Lake (1967) pointed out that the mere presence of prey items in the guts of alien fish species does not provide information about the severity of the effects of predation on the prey. Consequently, dietary studies on alien fish often need to be accompanied by some assessment of the effects by which increased predation on prey can affect native fish. Townsend (2003) undertook such an exercise in his study on the impact of brown trout on native fish in New Zealand. He found that brown trout feeding behaviour in streams has probably changed the daily timing patterns of emergence of benthic invertebrates considered to be preferred prey items of native fish. Such changes in invertebrate prey behaviour induced by trout foraging could render the invertebrates less available to native fish and hence reduce native fish production. They also potentially reduce invertebrate production.

Indirect impacts of alien fish on native species can be much harder to determine than direct impacts, especially given the need to demonstrate clear links between mechanisms and consequences at multiple levels and scales and, at the same time, avoid biases introduced by other co-varying factors. The main mechanisms by which introduced fish indirectly affect native species are through habitat removal or modification, including degradation in water quality. Such changes can, in turn, act as a stressor of native flora and fauna, producing a secondary impact. However, degradation in water quality resulting from other activities or events may be far more pronounced than that attributed to alien fish. Moreover, the prevalence of alien fish often occurs where water quality and native fish habitat are degraded (Kennard et al. 2005). This may indicate that alien fish are better able to tolerate degraded water quality than native fish, or that alien fish are often introduced to waters after the water quality has become degraded (e.g., from land-use changes in the catchment or pollution). The most notable examples of attempts to infer indirect impacts of established alien fish in Australia on native fish have been the assessments of carp impacts on turbidity and cyanobacterial bloom generation in Australia’s waterways and, to some extent, the impacts of tilapia (*Oreochromis mossambicus*) on turbidity. Such studies have more of a focus on water quality than on native fishes, although some authors acknowledge the potential negative effects of increased turbidity (and by virtue, sedimentation) on fish spawning habitat and the smothering of native fish eggs. In the case of the potential for carp to influence the prevalence of cyanobacterial blooms, other potential impact mechanism pathways have been put forward and include grazing of zooplankton that feed on these algae (top-down process) and the excretion of nutrients, many of which are derived from feeding on benthic flora and fauna that otherwise aren’t grazed by native fish (bottom-up process) (Gehrke and Harris 1994). It is an extremely complex process to determine which impact mechanism has more influence on the outcome in this case, let alone to gain quality evidence for even one of these mechanisms. However, studies like that carried out by Gehrke and Harris (1994), which are based on dietary studies of carp and native fish at a range of life stages and which provide conservative estimates of excretion rates for carp based on other benthophagous species, provide a weight of evidence for the probable relative (if not absolute) influence of zooplankton grazing and excretion on cyanobacterial blooms. In natural ecosystems there is typically a high degree of autocorrelation among key variables that can confound the ability or workers to provide unequivocal evidence of causative links where indirect impacts are concerned.

3.8 Triple bottom-line assessments

Another trend that has emerged from our review of the literature on impacts of alien fish on native fish is the increasing importance of triple bottom-line impact assessments (i.e. assessments of economic and social as well as environmental impacts). Admittedly, such studies are somewhat limited when it comes to ecological impact assessments in Australia (with the possible exception of activities that trigger the EPBC Act) and most of the articles we canvassed were from the scientific literature (i.e. peer-reviewed journal papers). Triple bottom-line studies appear more common where alien fish species are to be introduced to supplement fisheries stocks or to control aspects of the environment such as mosquito larvae or the prevalence of aquatic weeds. For these species, the social and economic benefits of the introductions can be more important than the environmental consequences of the introduction. Reports by Arthington & Blühdorn (1995) and Arthington & Mackenzie (1997) are Australian examples of studies that have attempted to present impacts of alien fish species in a triple bottom-line context, though unfortunately these reports do not cover many of the 23 species being investigated as part of this study. The NSW National Parks & Wildlife Service Threat Abatement Plan for *Gambusia holbrooki* (NPWS 2003) is another Australian example of a publication that covers economic and social aspects as well as outlining ecological impacts; though in this report reference to both economics and social aspects was made only in relation to control options.

The social and economic value of releasing ornamental fish into the wild is assumed to have little significance. Releasing such fish into the wild may make some people feel comfortable about not killing them. For others, the release may be deliberate and motivated by personal gain. Such positive social and economic outcomes are likely to be limited. A better understanding of the niches these species fill and of their interactions with ecological maintenance processes may ultimately reveal that, in some circumstances, some of the 23 established species perform ecological services not yet known to us. Some research into such questions is possibly warranted as such positive impacts need to be weighed against the negative ones.

3.9 Recommended approaches for ornamental fish in Australia

Ideally, in the case of ornamental fish established in the wild in Australia, the ‘burden of proof’ will be determined at a species level and agreed upon in advance by stakeholders before studies are approved and funded. Given that 23 species need to be assessed, a priority ranking is be required based on a risk assessment incorporating both the potential ecological damage and the risk of spread.

For ornamental fish species with limited wild populations, a site-led approach can be used to determine whether eradication or control of spread is required. This is because eradication will be less costly at the early stage of an incursion than after the species has spread more widely. In this respect a site-specific risk assessment is probably the best approach and this should focus on identifying potential vectors (natural and anthropogenic) that can potentially spread the species from the site(s) and, while focussing on containment, should also develop hypotheses of potential impacts which can then be tested at the site.

The correlative approach is unlikely to provide a viable impact assessment approach for the species with limited distributions, and a mechanistic approach, based initially on microcosm and mesocosm experiments is considered more appropriate.

There are numerous knowledge gaps on the impacts of the 23 listed ornamental fish species in Australia. As indicated earlier, it is always ideal to combine elements of impact mechanism, impact consequence and impact manifestation when undertaking investigations into the ecological effects of alien fish species on native fish. Prior to the implementation of any such studies, conceptual models describing the interactions between these elements should be developed so that testable hypotheses can be more easily derived. It is only through testing hypotheses that researchers are able to provide certainty to resource managers with respect to the significance of environmental impacts. However, the need for a given level of certainty will depend on whether resource managers, with the general consensus of key stakeholders, are prepared to opt for a precautionary approach to managing the impacts of alien fish (including established ornamentals) in Australia. If this is the case, then all that is required is for researchers to be able to demonstrate that at least one of the main indicators of an impact's occurrence has occurred in association with a particular fish species or fish community[3]. The advantage of this is that impact mitigation measures can be put into place earlier than if the full nature and ramifications of the impact(s) were to be determined; something that may be impossible to achieve. A disadvantage of this is that a lack of understanding about the full nature of the impact may hamper the ability of resource managers to implement appropriate mitigation measures. Moreover, studies of the impacts of these established ornamentals in native Australian habitats will apply only to the habitats where they are established, and they may be uninformative or of only limited use across the range of habitats into which they can potentially be introduced and become invasive (i.e. assessments of existing impacts may be inadequate to make judgements on broader-scale impacts).

Eradication of highly restricted populations without good evidence of impact might be considered prudent and precautionary if the cost of this is low and if eradication is feasible. Therefore an appraisal of the possibility for this would also be warranted for

[3] i.e. that there is some evidence from correlative, mechanistic or other approaches that supports the occurrence of an impact.

some species. This assumes that the cost of eradication at one or two sites will be less than the cost of efforts to determine whether impacts are occurring or not. This would involve a socio-economic and technical appraisal of the feasibility of eradication and is essentially a precautionary approach based on cost-benefit considerations.

For the species with multiple populations and widespread distributions, the cost of control and/or eradication can be expected to be much higher. For such species it is likely to be too late to consider eradication given the current control technologies available. A species-led approach to determine the existence or not of widespread problems is therefore warranted to identify whether management action (e.g. containment) is appropriate as well as what management actions are needed. A correlative approach maybe feasible for some of these species, but this assumes good data have been collected on at least some environments before the introduction and that these will allow a **Before** and **After** comparison. It also assumes that there will be comparable environments where the species has not been introduced to that can act as **Control** (or reference) sites and so provide a **Control** versus **Impact** comparison. If such sites exist, a full or partial BACI approach may be warranted.

If a BACI approach is feasible, the issue of what variables to measure and what hypotheses to test then arises. A more generalised, species-based risk assessment approach, coupled with micro- and mesocosm experiments, is likely to be the best way of identifying these. But as the results of tank or mesocosm experiments might not adequately reflect what could happen on larger scales, or in the natural environment, where a much more complex set of processes and interactions is likely to occur, a mechanistic approach is then required to provide adequate proof of impact, or to prove that there is no significant impact. This will need to address scale effects as a proven impact in one site won't necessarily occur at all sites. Investigators should therefore be encouraged to find several 'natural' field experiments. Multiple sites for impact analysis also create opportunities to see whether impacts can be reduced if the introduced species density is reduced and *vice versa*. Townsend (2003) used such phenomena to great effect in his study. These situations may not exist but designs based around natural experimental scenarios are likely to provide the most reliable evidence of impact, so are well worth looking for.

A key consideration for any assessment of impacts of alien fish that focuses on changes in relative abundance or species composition in the wild is that monitoring of these parameters should incorporate appropriate capture techniques and levels of effort to ensure the information is as robust as possible. Pilot studies may need to be carried out for some of the 23 established ornamental fish species to determine the most appropriate gear types for sampling them and the levels of sampling effort required to reliably detect changes in their abundance. This development of sampling methods is also required for studies aimed at establishing their presence or absence in waters not yet sampled (see chapter 2).